Sustainability Science
https://doi.org/10.1007/s11625-023-01400-6

ORIGINAL ARTICLE

Tree diversity and social–ecological resilience of agroforestry after volcanic ash deposition in Indonesia

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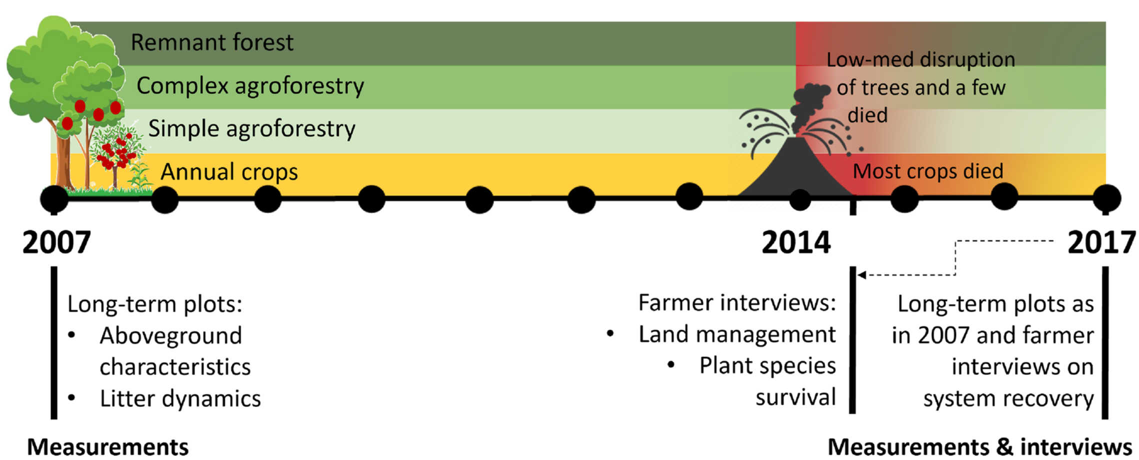
Received: 11 January 2023 / Accepted: 6 August 2023

Abstract

Smallholder farmers and their agroecosystems in active volcanic landscapes need to deal with and recover from eruptions. Resilience to extreme shocks may increase with system diversity, enhancing food and income security and ecosystem services provision; however, the longer term effects of volcanic ash are rarely assessed. To test the hypothesis that tree diversity contributes to the social–ecological resilience of coffee-based agroforestry, we quantified (1) the immediate effects of deposition of a 15-cm ash layer on tree survival, (2) the effect of volcanic ash on aboveground C stocks, tree diversity and wood density frequencies, (3) litter layer dynamics, and (4) farming system and income recovery 3 years after. Observations in four land-use systems before and after ash deposition (remnant forest, coffee-based complex and simple agroforestry, annual crops) were complemented by 46 farmer interviews on tree species' survival, system, and financial recovery. Based on farmer interviews, low-wood-density trees were most affected by volcanic ash deposition. Ash deposition did not, after 3 years and across land-use systems, significantly change tree density, basal area, or C stocks. In contrast, species richness in coffee-based agroforestry increased significantly. Standing litter stocks in agroforestry decreased, but slower decomposition partially compensated for reduced litter input. Farmers stated that diversity and flexibility in coffee-based agroforestry support a system recovery that is faster than that for annual crops, suppressing income fluctuation. Farmer's adaptive responses to enhance species diversity contributed to the resilience of farms, by retaining basic system structure and functions of agroforestry, and increasing product diversity and income.

Graphical abstract



Keywords Carbon stocks · Disaster · East Java · Farmer income · Litter layer · Mount Kelud · Recovery · Tree survival

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Published online: 22 August 2023

Introduction

Among the diverse roles of biodiversity for human well-being (Díaz and Malhi 2022), trees and their diversity play a special role as they shape the landscape, modify climate and water flow, and influence most environmental services from the agroecosystem (Altieri 1999; Ifejika Speranza 2013; van Noordwijk et al. 2019, 2022). While climate-related extreme events (such as extreme drought, flooding, and fire) increase in magnitude and frequency, 'natural' shocks (including tectonic activity, volcanic eruptions and ash deposition) have in specific environments since long been a challenge to the sustainability and resilience of social–ecological systems (Folke et al. 2004; Steffen et al. 2018; Yi and Jackson 2021). Recovery of vegetation after volcanic ash deposition is essential in re-establishing the ecosystem (Fiantis et al. 2019) and the human livelihoods it supports; in areas with a high frequency of such events we may expect that resilience has emerged as a social–ecological system trait.

Beyond its ecological meaning of 'bouncing back' after disturbance as has been studied from coral reefs to forests (Baho et al. 2017; Brand and Jax 2007; Folke 2006; Meerow and Newell 2019; Trumbore et al. 2015; Yi and Jackson 2021), resilience has also been considered as an aspect of agroecosystems (Lin 2011) and of social–ecological systems from local to global scale (Carpenter et al. 2014; Folke et al. 2016; Turner et al. 2022). 'Bouncing back' after a shock can, however, mean being trapped in a system without opportunities to meet aspirations of sustainable development, and 'bouncing forward' may sound more appealing (Hynes et al. 2020). The definition of resilience, when applied to social–ecological systems, has been expanded to the capacity to absorb shocks and adapt to, or transform in the face of unexpected change while retaining the same basic structure and ways of functioning that support human well-being (Berkes et al. 2003; Biggs et al. 2015; Chapin et al. 2010; Folke 2006). Resilience in social–ecological systems requires a human (social) adaptive capacity to interact with ecological sustainagility (van Noordwijk et al. 2022). Human actions that maintain, innovate, and improve development on current pathways are prove of adaptive capacity (Folke et al. 2010; Walker et al. 2004). Sustainagility refers to sustaining the ecological resource base that allows the social adaptive capacity to be expressed (Jackson et al. 2010); it may be based on retaining components with potential future utility that exceeds their current use. The hypothesis that higher levels of retained (agro)diversity support resilience (Jackson et al. 2012; Vandermeer et al. 1998), although conceptually appealing, still requires empirical testing.

There has been a call for further empirical evidence about the association between agroforestry and resilience from academic and development communities (Garrity 2012; Lin 2011) or even 'treesilience' (Leeuw et al. 2014). While counter-examples exist, where fast-growing, shallow-rooted trees increase rather than decrease climate risk for intercropped cacao (Abdulai et al. 2018), agroforestry systems reportedly enhance livelihood resilience in the face of climate change (Gnonlonfoun et al. 2019; Jacobi et al. 2015; Nyong et al. 2020; Pérez-Girón et al. 2020), and floods and drought (Quandt et al. 2017). Through tree diversity, agroforestry can provide insurance, or a buffer, against environmental fluctuations, maintaining the system's functional capacity against disturbance (Hutchison et al. 2018; McCann 2000; van Noordwijk et al. 2019), but factual evidence is largely contextual.

Empirical studies of agroecosystem resilience that match the formal definitions are understandably scarce, as they require studies (and understanding) of system functioning both before and after an (unpredictable) external shock and teasing apart the ecological resource properties and human adaptive change that supported a shift in the development trajectory while retaining basic structure and functions. In the immediate aftermath of an unpredictable external shock, disaster response and support prevail over detailed scientific data collection and ethical considerations apply. The response to shocks may well depend on specific aspects of the shock involved. Ecological shocks can start from underlying geological structure (e.g., tectonic or volcanic activity), with potentially global climatic consequences (Robock 2000), ocean–land climatic interactions [e.g., typhoons (hurricanes), extreme rainfall events triggering landslides and floods], or invasive species (including pests, diseases, weeds). The gradual process of global climate change can trigger shocks, e.g., shifting temperature and precipitation patterns disturb coffee's flowering (Sujatmiko and Ihsaniyati 2018), destabilizing production and harvesting time (Haokip et al. 2019; Weldemichael and Teferi 2019). Climate-induced complete crop failure has also been reported (Challinor et al. 2010; Goulart et al. 2021). Social shocks can start with markets, e.g., through the collapse of tourism after terrorism or pandemics, such as COVID-19 (Duguma et al. 2021), trade wars between countries or new certification requirements. Being prepared for such specific events that can differentially impact the various components of local livelihoods is not possible and more generic 'resilience' may have to cover the unpredictability of shocks, which in hindsight usually lead to opinions on 'inadequate preparation'.

As a home to more than 100 active volcanoes, most of the most-fertile agricultural land in Indonesia is around volcanoes, explaining their high human population density (Brown et al. 2015). Mt. Kelud in East Java, Indonesia, one of the active volcanoes which erupted more than 30 times since 1000 AD, erupted most recently in 2014 (Maeno et al. 2019b; Nakada et al. 2016; Nawiyanto and Nurhadi 2019) and precipitated volcanic ash in the surrounding area. Mt. Kelud is located in a highly populated area of more than 800 people per km^2 in 2020 (Saputra et al. 2022), and has an eruption cycle of less than 30 years (Indriyanto et al. 2023; Maeno et al. 2019a). Eruption events severely impact—at least in the short term—land-use systems in the surroundings, including coffee-based agroforestry systems. Ash deposition changes soil properties and quality in coffee-based agroforestry systems through decreased aggregate stability and infiltration (Anda et al. 2016; Blong et al. 2017; Saputra et al. 2022), leading to a decrease in coffee bean production (Ishaq et al. 2020b). This sudden shock can alter aboveground characteristics, litter layer dynamics, and farmer management, which could affect how the systems function. As detailed process studies in local coffee-based agroforestry had been completed before the 2014 eruption of Mt. Kelud, an opportunity arose to document farmers coping strategies and resilience, as well as resilience at the tree level and the recovery of soil-mediated functions, such as a protective litter layer (Sari et al. 2022). Land-use change and protection in the densely populated Kali Konto watershed have been studied for the past 40 years (Lusiana et al. 2012; Nibbering 1993; Thalen and Smiet 1985). After the Mt. Kelud eruption of 2014, a resilient indigenous non-legume nitrogen-fixing tree (*Parasponia rigida*) helped stabilise the volcano's upper slopes and was reported to be an option to improve soil fertility in coffee-based agroforestry systems (Ishaq et al. 2020a, b). Soil properties in coffee-based agroforestry systems recovered faster (6 years after eruption) than in annual crop systems (Saputra et al. 2022). However, to what extent the aboveground component of agroforestry system changes, which may affect its functioning and social–ecological resilience to volcanic eruptions, remains poorly understood.

In this study, we assessed the effects of a volcanic eruption on vegetation characteristics and farmer income across a land-use gradient ranging from remnant forest, complex and simple coffee-based agroforestry systems to annual crops in the Kali Konto area to test the hypothesis that tree diversity contributes to the resilience of agroforestry systems through differential responses to external shocks and increased options for farmers to secure income. We explored the immediate effect of the volcanic eruption on tree species survival based on farmer interviews and assessed the recovery of the system 3 years after the eruption based on plot measurements before and after the eruption. We address the following research questions: (1) How does the survival of plant species vary among coffee-based agroforestry and annual crops systems in their response to an immediate effect of the volcanic eruption? (2) Does the volcanic eruption affect aboveground C stocks, tree diversity and mean wood density (WD) across the land-use gradient? (3) How do the annual litter input, decomposition rate, and standing litter stocks change in response to a volcanic eruption in coffee-based agroforestry systems? (4) Does the capacity to recover from a volcanic eruption at the system level vary across the land-use gradient?

We hypothesized that annual crops will be severely damaged in response to volcanic ash deposition, while tree species in agroforestry systems, particularly those with high WD, will be less affected, because dense stems (and leaves) may better endure damage (Niklas and Spatz 2010). We expected that basal area, plot-level WD and the range in WD, aboveground carbon stocks, and tree diversity will decrease in response to the volcanic eruption in all land-use systems because of tree mortality in response to the eruption. We expected that standing litter stocks in coffee-based agroforestry systems will decrease in response to the eruption, because a lower basal area leads to a lower litter input, although lower litter quality may slow down the decomposition rate. At the system level, we expected that agroforestry systems will recover faster than annual crop systems, in terms of both vegetation characteristics and farmer income. We expected that agroforestry systems are more resilient to volcanic ash deposition, because trees are more resilient to ash deposition than annual crops, and that a higher tree diversity will support a faster recovery.

Methods

Study site

Field work was conducted in the Kali Konto watershed, which is geographically located at 7° 45′ 57″–7° 56′ 53″ S and 112° 19′ 18″–112° 29′ 57″ E, with elevations ranging from 600 to 2800 m above-sea-level (m a.s.l.), in the Ngantang Sub-district, Malang Regency, Indonesia. This area is located about 13–15 km north (and north–east) of Mt. Kelud (7° 55′ 48″ S–112° 18′ 29″ E) and is, depending on prevailing winds at the time of eruption, impacted by the deposition of volcanic material, while volcanic eruptions occur at least every 15–30 years (Ishaq et al. 2020b). The climate in the Kali Konto watershed has tropical monsoon characteristics. There is a rainy season from November to March, while the dry season in most years lasts from June to October (Saputra et al. 2022). Annual precipitation varies from 2995 to 4422 mm $year^{-1}$, and the annual average temperature from 20 to 22 °C (BMKG 2018). Coffee is one of the important commodities in this area and frequently found throughout the landscape in agroforestry systems. Most of these systems are managed by smallholders with little fertilizer input and low management intensification. Most coffee-based agroforestry systems occur on slopes of 11–23%, at altitudes from 750 to 950 m above sea level (Saputra et al. 2022).

Plots were established based on stratified sampling along a local land-use intensity gradient in 2007/2008, and the same plots were revisited and resampled in 2016/2017, 3 years after the Mt. Kelud eruption in 2014. We performed interviews with farmers in 2017 to evaluate the immediate effect of volcanic ash deposition in 2014 on individual plant survival, and to assess total system performance 3 years after the eruption. Four land-use systems were selected: remnant forest (RF), complex coffee-based agroforestry systems (CAF), simple coffee-based agroforestry systems (SAF), and annual crops (CR). We defined an agroforestry system as a combination between cash crops (coffee) and shade trees which had a relative basal area of the main crop (coffee) of less than 80% (Hairiah et al. 2006; Sari et al. 2020). The coffee-based agroforestry systems with 2–4 shade tree species, but where coffee accounted for more than 50% of the total basal area (BA) of woody species, were classified as simple agroforestry, whereas systems with at least five different shade tree species were classified as complex agroforestry (Hairiah et al. 2020; Mulyoutami et al. 2023). The common shade trees in coffee agroforestry systems in the region are fruit–trees, such as *Durio zibethinus* (durian), *Persea americana* (avocado), *Lansium domesticum* (langsat); timber or fast-growing tree species, such as *Gliricidia sepium* (gamal) and *Falcataria moluccana* (sengon). Four plots of 20 m × 100 m were established in each land-use system. Plots had a similar soil type (inceptisols) and slope (average gradient of 40%, 11%, and 2% for RF, CAF and SAF, and CR, respectively) within the land-use systems.

Due to a similar distance between the Mt. Kelud volcano and the study locations, research plots likely received comparable amounts of ash, with a similar composition, during the most recent eruption (Cutler et al. 2016). In the study sites (Ngantang sub-regency), 10–20 cm of volcanic ash was deposited (Nakada et al. 2016). After eruption, CAF and SAF farmers manually removed the volcanic ash near the tree trunk. They applied organic (2.5–3.5 Mg ha^{-1} manure year^{-1}) and inorganic fertilizers (120 kg N, 30–60 kg P, and 30–60 kg K ha^{-1} year^{-1}). In contrast, in CR, some farmers mixed the soil and volcanic ash using a small hand tractor and applied twice higher organic and inorganic fertilizer than in agroforestry systems (Saputra et al. 2022).

As the addition of volcanic ash in coffee-based agroforestry and other land-use systems is expected to disturb the systems ecologically and economically, we conducted an interdisciplinary study, involving both an ecological and a social component. Volcanic ash deposition can disturb and eliminate ash-intolerant trees and crops, altering the system structure, such as tree density and basal area, and, therefore, the capacity of the system for carbon sequestration. Species composition and diversity of the systems may also change, as tree survival is expected to increase with species WD (Greenwood et al. 2017). In addition, volcanic ash deposition might inhibit tree growth, which together with the decrease in tree density, may decrease litter production and decomposition rates. Thus, volcanic ash deposition may also alter the function of the litter layer to protect the soil surface. For these reasons, from an ecological perspective, we measured the change in coffee-based agroforestry systems in terms of their structure (BA, WD, tree density) and functions (diversity conservation, C sequestration, litter production and soil protection).

Those ecological changes, however, cannot be separated from farmer involvement as land managers. Thus, as a social component we performed in-depth interviews with farmers to link the results of these to the ecological measurements. As such, we can enhance the understanding on the impact of ash deposition on the ecological system (tree and ecosystem level), as well as on the social system based on the farmer's point of view, and the economic recovery of the systems.

Ecological measurements

Basal area and tree diversity

We measured the diameter at breast height (DBH), 1.3 m above soil surface, of all trees > 5 cm DBH in a subplot of 20 m × 20 m, while we measured the DBH of trees > 30 cm DBH in the entire 20 m × 100 m plot. Trees were identified to species. We calculated tree density (the number of trees per ha), plot basal area and rarefied tree species richness as a measure of tree diversity. Plot basal area was calculated as the proportion of the area occupied by trees per ha (m^2 ha^{-1}) as $\sum \pi(\mathrm{DBH}/2)^2/\text{plot area}$, where DBH is the diameter at breast height (1.3 m) of each tree. Bootstrapped species richness, calculated using the 'rarefy' function in the vegan R package (Oksanen et al. 2022) based on Hurlbert (1971) and Heck et al. (1975), was used to obtain the expected number of species per 40 stems.

C stocks and wood density

Aboveground tree biomass was estimated based on allometric equations. We used species-specific allometric equations for several species found in agroforestry systems (Table A.2), such as pruned coffee, banana (Arifin 2001), and palms (Brown 1997). For the other trees, we used a general allometric equation for humid tropical forests (Chave et al. 2005). The aboveground C stock per ha was calculated by converting the biomass into carbon by multiplying by 0.46 (Hairiah et al. 2011). The WD value of each species was obtained from the wood density database from the World Agroforestry Centre (http://db.worldagroforestry.org/wd). Plot-level mean WD was calculated as $\sum_i^n \left(\mathrm{WD}_i * x_i\right) / \sum_i^n x_i$, where WD_i is the wood density of species i, and x_i is the weight/number of species i. The range in WD per plot was calculated as the difference between the

10th and the 90th percentile of the WD values of all stems in a plot to minimize the effect of one or a few stems with very high or low WD. We included both coffee and shade trees when calculating tree density, basal area, tree diversity and C stocks in the plots.

Litter layer measurements: litter production, litter quality and standing litter stocks

Litter production was measured for 1 year before and after the eruption, using litter traps. Two traps of 1.5 m × 3 m, with a 1 mm-mesh size, were placed below the canopy of each plot (Hairiah et al. 2006; Sari et al. 2022). Litter was collected weekly. Litter dry weight was determined by oven-drying the litter samples for 48 h at 60 °C (Negash and Kanninen 2013). To assess litter quality, we measured the N content, lignin and polyphenols content of each of the litter samples following the methods of Kjeldahl (Gallaher et al. 1976; Goering and Van Soest 1970; Ingram and Anderson 1993, respectively). A 0.5 × 0.5 m frame was used to collect standing litter samples at ten locations within each subplot. Litter samples were dried in an oven for 48 h at 60 °C.

Litter decomposition experiment

The decomposition experiments were conducted by comparing the decomposition rates of litter collected in three different land-use systems (RF, CAF, SAF) across coffee-based agroforestry systems (CAF and SAF). Litter from CAF was composed of a combination of *Coffea canephora*, *D. zibethinus*, and *P. americana* leaves, while the SAF litter was composed of a combination of coffee and *Gliricidia* leaves. The litter of the different species was mixed in equal proportions. The litter was stored in litter bags which were 25 cm × 30 cm in size and had a mesh size of 2 mm (Ingram and Anderson 1993). The quantity of litter was equivalent to the annual litterfall input, which is 8 Mg ha^{-1}. A total of 120 litter bags (two land-use systems, three types of litter, four replicates, and five observations in time) were placed in CAF and SAF. We measured the remaining litter mass at 1, 2, 4, 8, and 16 weeks after the start of the experiment, including the soil temperature and water content, following a similar approach as in Sari et al. (2022).

We estimated the decomposition rate using a temperature-corrected exponential decay function to compare the decomposition rates across different agroforestry systems at the same temperature, modified from Olson (1963) $= \left(X_t/X_0\right) = \mathrm{e}^{-kI_t t}$, where X_t is the proportion of initial mass remaining at time t (in g), X_0 is the proportion of initial mass (in g), k is the decomposition rate (k; week^{-1}), t is time (in weeks), and I_t is an index of temperature effects based on the average over the n weeks of the measurement period (Sari et al. 2022). I_t was calculated as the product of daily values, as $\left(\Pi_1^n Q_{10}^{(T-T_{\mathrm{ref}})/10}\right)^{1/n}$, where Q_{10} is the temperature response rate of biological processes, T is the temperature (in °C), and T_{ref} is a reference temperature of 20 °C. A Q_{10} of 2.2 was used as an appropriate estimate of Q_{10} for agricultural soils (Delogu et al. 2017).

Social methods: farmer interviews on the performance of trees and agroforestry systems

We conducted informal, semi-structured interviews of approximately 50–60 min with farmers to assess the survival level of tree species and agroforestry systems in response to the volcanic eruption. In total, we interviewed 46 smallholder agroforestry farmers, who (previously) owned or managed both agroforestry systems and annual crops, 3 years after the Mt. Kelud eruption (2016/2017). We conducted interviews with the 12 farmers who manage the plots that we included, and we invited 34 more farmers using random sampling methods to include more of the variation in the landscape. First, each participant was requested to assess the immediate effect of volcanic ash deposition at the level of individual tree species in coffee-based agroforestry systems in three categories: (1) the disruption (damage or mortality) of individual tree species; (2) (total) income recovery; and (3) production stability, including the time needed to return to the conditions before the eruption. Income recovery for each tree species refers to whether the amount of income for a species was similar to the income that a farmer generated for that species before the disturbance. Production stability refers to the stability in the production at the species level from directly after the disturbance until the time of observation. For each category, we used specific indicators that farmers scored from 1 (very low) to 5 (very high) for each tree species (Table A.1). During this interview, we differentiated tree species based on three routes: planted (deliberately planting), voluntary/tolerated (spontaneously growing), and forest tree species (maintained forest tree).

Second, the same participants were requested to assess the capacity of agroforestry systems to recover from a volcanic eruption at the system level 3 years after the eruption in two categories: (1) farming system recovery, and (2) income recovery (Table A.1). Farming system recovery in this study refers to the ability of the systems as a whole to recover to similar performance as before the eruption. We used several indicators to estimate the farming system recovery level, such as the disruption level, the time to recover to pre-disturbance conditions, and management intensification. We asked each farmer to score the overall (ecological) disturbance level of the system, representing vegetation, litter, and soil characteristics. Time to recover to pre-disturbance condition refers to the time needed by the system to reach similar production levels and ecological functioning as before the disturbance. Management intensification indicated the amount of effort needed to avoid negative effects of ash on plant growth, by, for example, mixing the ash into the soil (labour and equipment), and the amount of fertilizer needed. Farmers also scored these indicators at a scale from 1 (very low) to 5 (very high). However, we also included an open question about the time needed for recovery both at the tree species and at the system level. Income recovery at the system level refers to whether the income from coffee-based agroforestry after the eruption was similar to the total income that a farmer generated before the disturbance. It was evaluated based on two indicators: (total) income and savings. (Total) income refers to the total earning generated from all products derived from the system in the observed year, excluding the production and labour cost. We could not use "net income" as the indicator, as only few participants were willing to specify the exact production and labour cost during the interview. The amount of savings, on the other hand, refers to whether farmers can set aside part of their income after paying their regular bills. We calculated the final score for each category by averaging the scores of all indicators in that category. In addition, we asked farmers (1) what their reasons were for choosing a particular land-use system, and (2) how they responded to the disruption, and why they responded in that way.

Statistical analysis

We used linear mixed-effects models to evaluate the effect of the volcanic eruption and land-use systems on (1) the aboveground characteristics, tree diversity, and C stocks across the land-use gradient; and (2) standing litter, annual litter production, litter quality and decomposition rates within agroforestry systems. Land-use system, year and their interaction were included as fixed effects, and a random intercept per plot was included. We compared models based on all different combinations of the effects, and selected the best model based on the lowest Akaike Information Criterion (AIC) value. To determine the significance levels of the fixed effects, we calculated bootstrapped confidence intervals. We fitted a linear regression model to evaluate the relation between (1) plot-level mean WD and litter layer characteristics (standing litter, annual litter production, and litter quality), (2) species-level WD and the species-specific scores of the disruption level, income recovery and production stability, and (3) rarefied species richness and farming system recovery and economic recovery at the system level after eruption. To test the difference in recovery level scores regarding the farming system and economic recovery between land-use systems, we performed one-way ANOVAs, followed by Tukey's HSD post-hoc tests. All statistical analyses were performed in R 4.2.0 (R-Core-Team 2022).

Results

Immediate effects of the volcanic eruption on the survival of plant species across land-use systems

Based on farmer observations, most tree species in complex and simple coffee-based agroforestry systems survived after volcanic ash deposition with light to medium damage, but trees of a few species died. The disruption level due to the volcanic eruption varied among tree species in agroforestry systems, the average score was 1.5, but ranged from 1 (low) to 3 (medium). We found that tree WD was negatively associated with the disruption level (Fig. 1a). Species with high WD, such as fruit trees, such as *Nephelium* spp., *L. domesticum*, *Gnetum gnemon*, *Syzygium aromaticum*, *Curculigo* sp., and timber species, such as *Swietenia mahagoni* and *Hibiscus* sp., had the lowest disruption level (score 1). Low WD species such as *Musa* spp. and *Carica papaya* had the highest disruption level (scores 4–5), and *Cocos nucifera* was severely disrupted, most individuals of this species died. The disruption level was positively correlated with the time needed for recovery (Pearson's $r = 0.36$; $P < 0.05$). Overall, the time needed for tree species to recover from the disruption varied from 9 to 36 months. Income recovery and production stability of tree species tended to increase with WD (Fig. 1b, c). We did not find significant differences in the disruption level, production stability and income recovery between planted, voluntary/tolerated, and forest tree species. Multi-purpose shade tree species that provide multiple benefits based on different parts of the tree (i.e., leaves, fruits, branches, stems), such as *D. zibethinus* and *P. americana*, were preferred by farmers. After eruption, the forest tree species *P. rigida*, *D. zibethinus*, and timber tree species (*S. mahogany* and *F. moluccana*) were planted in coffee-based agroforestry systems to replace dead trees or to fill in empty space to provide shade for the coffee plants. Farmers collected *Parasponia* seedlings from the nearest riverbank, where they germinated from seeds accumulated through the lava flow during the volcanic eruption (Ishaq et al. 2020a).

In contrast, most plants of crop species, such as rice, cabbage, chili pepper, tomato, and maize, were buried by volcanic ash and severely disrupted (scores 3–5, Fig. 2a). Ginger and curcuma, which are planted between coffee and shade trees in agroforestry systems, were less damaged (score 1). Rice was the most disrupted crop, followed by cabbage and chili pepper. After the eruption, most crop farmers switched to growing maize, which was less severely damaged. Farmers indicated that they could not grow crops during the first 6–12 months after ash

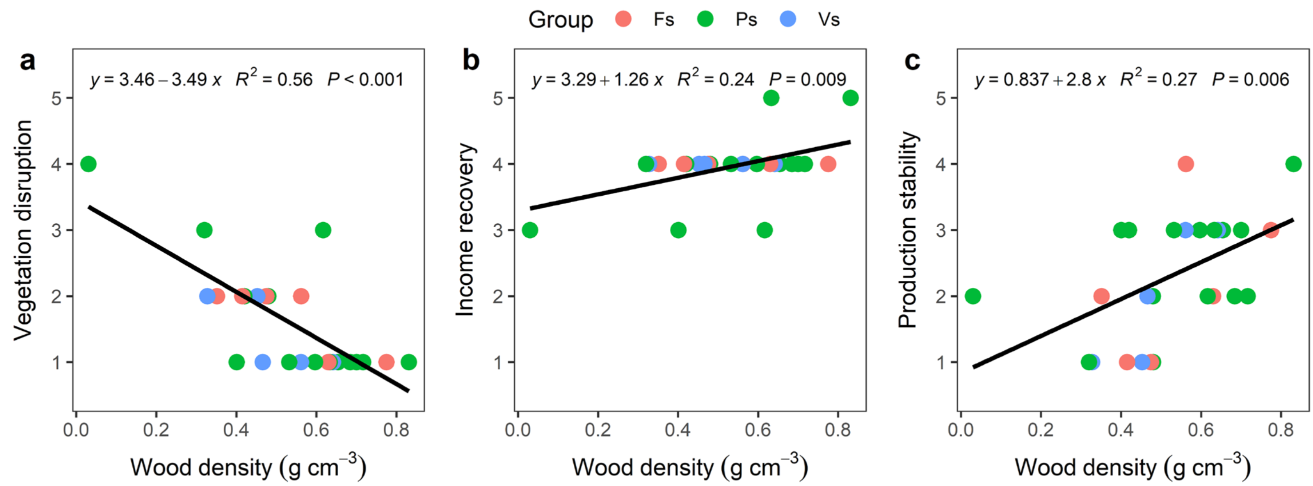

Fig. 1 Relationship between wood density and **a** disruption level, **b** income recovery, and **c** production stability of plant species in coffee-based agroforestry systems (score 1 = very low; 2 = low; 3 = moderate; 4 = high; 5 = very high; Fs = forest tree species; Ps = planted tree species; Vs = voluntary/tolerated tree species; NB: banana wood density is represented as 0.03 g cm^{-3})

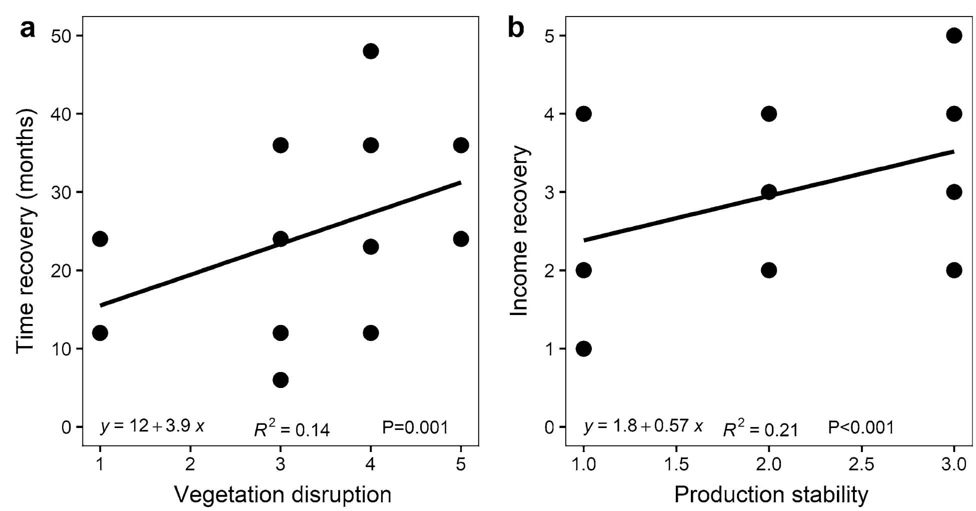

Fig. 2 Relationship between **a** disruption level and recovery time; **b** production stability and economic recovery of plant species in crop systems (score 1 = very low; 2 = low; 3 = moderate; 4 = high; 5 = very high)

deposition. High organic and inorganic matter input and ploughing were needed to prepare the soil to be able to grow crops. However, crop production was relatively low; only 24–36 months after the eruption production levels were comparable to those before the eruption. Production stability of crops tended to positively correlate with the economic recovery level (Fig. 2b).

Aboveground structure

Effects of volcanic ash deposition on tree density, BA, WD, C stocks, and tree diversity across a land-use gradient

We assessed the effect of the volcanic eruption on aboveground structure across the land-use gradient. Tree density, basal area, and aboveground C stocks differed significantly across land-use systems, but we found no effect of year, thus no difference between before and after the eruption, except for rarefied species richness (Table 1; Fig. 3). Rarefied species richness significantly increased with 47% and 66% in CAF and SAF, respectively, after the disruption. However, we found no significant change in rarefied species richness in RF (Fig. 3f). We found no effect of year on plot-level mean WD.

Species composition changes across the land-use gradient in response to volcanic ash deposition

Tree species composition varied between land-use systems and years. We found less stems of tree species with high WD, such as *Quercus lithocarpus*, after the eruption in most plots. Some species, such as *Anisoptera curtisii*, *Pterocarpus*

Table 1 Overview of the best linear mixed-effects model for the included aboveground vegetation structure variables and litter characteristics

Dependent variables	Best model
Tree density (number of trees ha^{-1})	LUS*, Year, LUS × Year
Basal area (m^2 ha^{-1})	LUS*, Year, LUS × Year
Aboveground C stocks (Mg ha^{-1})	LUS*, Year, LUS × Year
Plot-level mean WD (g cm^{-3})	LUS*, Year, LUS × Year*
WD range (g cm^{-3})	LUS*, Year, LUS × Year*
Rarefied species richness (number of species per 40 stems)	LUS*, Year*, LUS × Year*
Litter input (Mg ha^{-1})	LUS*, Year*, LUS × Year*
(L + Pp):N	LUS, Year*
Decomposition rate ($week^{-1}$)	LUS, Year*
Standing litter (Mg ha^{-1})	LUS*, Year*, LUS × Year*

LUS land-use system

*Significant difference at $P<0.05$ based on bootstrapped confidence intervals)

indicus and *Calliandra calothyrsus*, were not found in 2017. However, the pioneer tree species *Macaranga tanarius* was frequently found in almost all RF plots in 2017 (Table 2). We found that *P. rigida* was planted in CAF plots in 2017, confirming the results of the interviews that farmers planted this species after the eruption. In addition, more timber tree species, such as *Swietenia mahagoni*, *Anthocephalus cadamba*, *Hibiscus* sp., and *Toona sureni*, were planted in CAF. *Cocos nucifera* was less frequently found in CAF after a disruption. Whereas in SAF, the dominant species *Gliricidia sepium* was replaced by fruit trees, such as *D. zibethinus*, *L. domesticum*, *Artocarpus heterophyllus* and *Parkia speciosa*, and by fast-growing tree species, such as *F. moluccana*, *Leucaena leucocephala* and *Erythrina indica*. The change in tree species composition in agroforestry systems resulted in the modification of the WD range. The change in the WD range differed across land-use systems, as there was a significant interaction between land-use system and year (Table 1). The addition of fruit trees, such as *D. zibethinus* and *L. domesticum*, in SAF after the disruption (in 2017) increased the WD range, reaching 0.78 g cm^{-3} in some plots. Species composition did not change in the annual crops system after the eruption. However, the frequency of maize and Napier grass planted by farmers (for fodder) gradually increased.

Effect of volcanic ash deposition on litter dynamics in coffee-based agroforestry systems

We found that volcanic ash deposition altered most litter characteristics in agroforestry systems. Annual litter production significantly differed between agroforestry systems and years (Table 1). In CAF, litter production was higher before the eruption in 2007 (7.05 Mg ha^{-1}) than in 2017 (5.52 Mg ha^{-1}) (Fig. 4a), whereas in SAF litter production did not change in response to the volcanic eruption. Regarding litter quality, only litter (L + Pp):N content differed significantly between years. The average (L + Pp):N content in agroforestry systems in 2007 was 15.5 and increased to 25.9 in 2017 (Fig. 4b), indicating a decrease in litter quality. We did not find a difference in litter (L + Pp):N content among land-use systems. The decomposition rate before the disruption was higher (mean value of 0.033 $week^{-1}$, ranging from 0.020 to 0.061) than after the eruption (mean value 0.021 $week^{-1}$, ranging from 0.016 to 0.028). Volcanic ash deposition significantly decreased the decomposition rate (k value); the mean k value was 35% lower than in 2007 (Fig. 4c).

Standing litter stocks are determined by litter production and the decomposition rate, which is linked to litter quality. Standing litter stocks were significantly different between years and land-use systems. The standing litter stocks in CAF and SAF decreased significantly after the disruption, with approximately 30%, in both CAF and SAF (Fig. 4d).

The capacity of agroforestry systems to recover from the volcanic eruption based on farmer interviews

Based on the perspective of farmers, agroforestry systems recovered to a greater extent from the volcanic eruption at the land-use system level compared to annual crops, as they had a higher recovery score, but the recovery level did not significantly differ between SAF and CAF (Fig. 5a). Income recovery did not significantly differ among land-use systems (Fig. 5b). Smallholder farmers decided on a type of land-use system based on the position of a plot in the landscape and the flexibility of the system. Other, but less important, factors were the accessibility and size of the plot, time to harvest, and financial benefit (Fig. 5c). Most agroforestry farmers mentioned that flexibility was the main advantage of agroforestry systems, particularly because of the option to modify species composition. Other advantages were low maintenance, securing diversity and 'sufficient' continuous income. Farmers sometimes added certain plant species to the agroforestry system specifically for supplying spices or medicine for their own consumption, for material for ritual–cultural ceremonies, and for fodder for their livestock. We found a positive relationship between rarefied species richness and farming system recovery scored by farmers (Fig. 6a). The economic recovery of the systems 3 years after the eruption also increased with diversity, but the relationship was weaker (Fig. 6b).

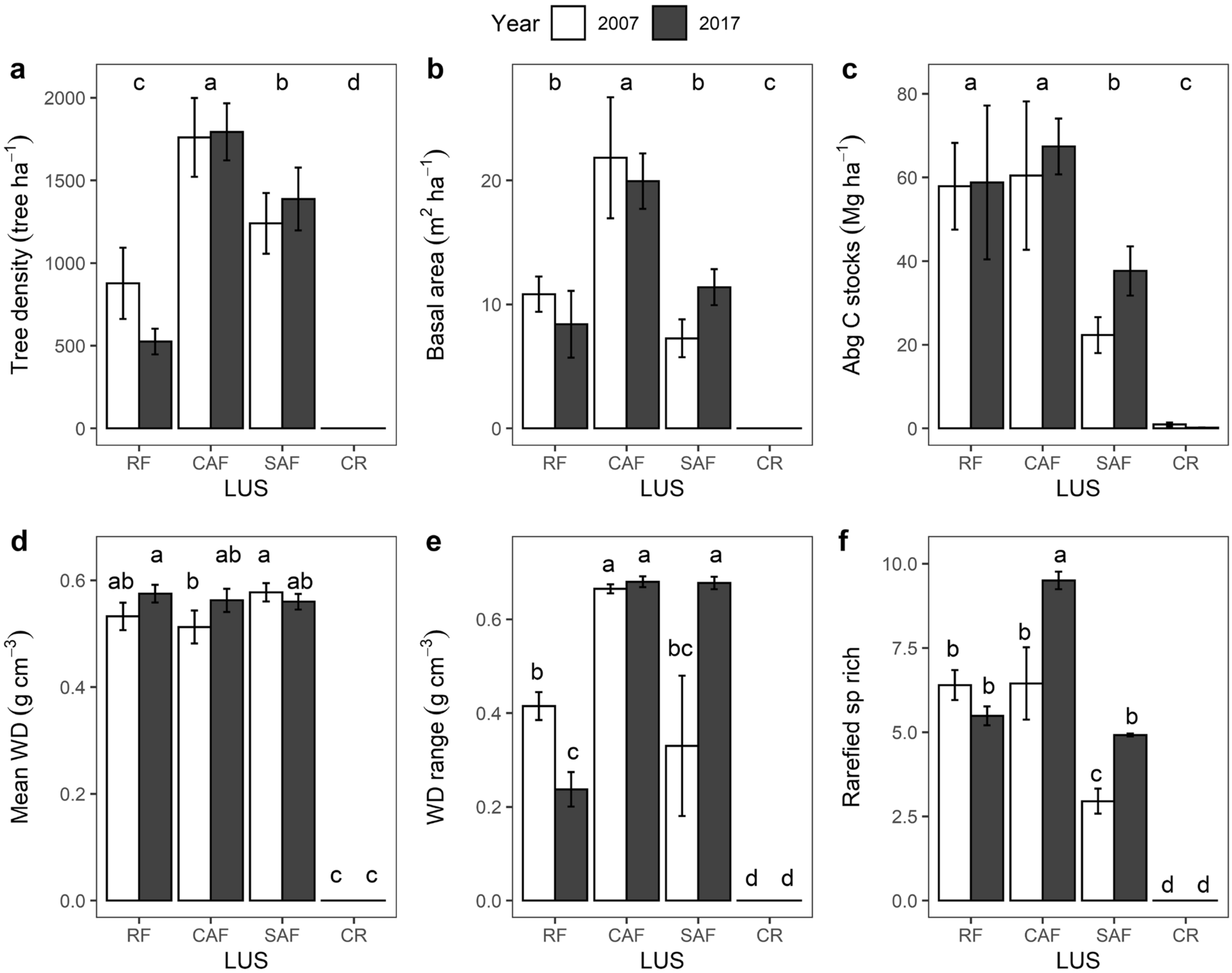

Fig. 3 **a** Tree density, **b** basal area, **c** aboveground C stocks, **d** plot-level mean wood density, **e** wood density range, and **f** rarefied species richness (the number of species per 40 stems) of various land-use systems before (2007) and after (2017) the volcanic eruption (*RF* remnant forest, *CAF* complex agroforestry, *SAF* simple agroforestry, *CR* annual crops, *LUS* land-use system. Different letters indicate significant differences ($P<0.05$), letters were placed above the bars in case of a significant interaction between year and LUS, or on top of the plot when there was a significant effect of LUS, but not of year

Discussion

A volcanic eruption may negatively or positively affect surrounding agricultural areas through ash deposition because of an immediate, damaging effect to crops, or long-term effects of nutrient addition from ash, respectively. In this study, based on farmer interviews, we found that the deposition of volcanic ash had a more significant immediate negative impact on annual crops and on tree species with low WD than on tree species with high WD. However, the aboveground structure did not change significantly in response to the eruption in any of the land-use systems, but tree diversity in agroforestry systems increased significantly. Litter dynamics in coffee-based agroforestry systems were altered, but a litter layer was present 3 years after the eruption still. Farmers mentioned that, in contrast to annual crop systems, coffee-based agroforestry systems facilitate quicker system recovery and reduce income variability, because agroforestry systems have a higher diversity of tree (plant) species.

Immediate effects of volcanic ash deposition on plant species survival across the land-use gradient

We expected that volcanic ash deposition up to 15 cm would severely damage crops, while tree species in agroforestry systems with high WD would be less severely disrupted compared to low WD tree species. Our results confirmed this hypothesis. Crops may be broken, buried, and possibly smothered by volcanic ash deposition, resulting in crop

Table 2 Plant species found in remnant forest and coffee-based agroforestry systems before (2007) and after the volcanic eruption (2017)

WD, g cm^{-3}	Scientific name	Local name	Group	Measurement: mean BA across all plots, m^2 ha^{-1} (value range)					
				Remnant forest		Complex agroforestry		Simple agroforestry	
				2007	2017	2007	2017	2007	2017
0.83	*Nephelium* spp.	Rambutan	Ps			2.06	0.78		
0.78	*Lansium domesticum*	Langsat	Fs, Vs, Ps	0.06		0.35 (0.19–0.52)	0.4 (0.16–0.81)		0.31 (0.12–0.53)
0.72	*Gnetum gnemon*	Melinjo	Ps			0.49 (0.35–0.64)	0.31		
0.71	*Quercus lithocarpus*	Pasang	Fs	0.56 (0.07–3.01)	0.55				
0.70	*Curculigo* sp.	Klerek	Ps			1.81 (1.79–0.84)			
0.70	*Syzygium aromaticum*	Cengkeh	Ps				0.06		
0.68	*Gliricidia sepium*	Gamal	Ps			0.45 (0.20–1.24)	0.22 (0.09–0.69)	0.25 (0.10–0.9)	0.11 (0.06–0.19)
0.67	*Pterocarpus indicus*	Sonokembang	Fs	0.35 (0.17–0.53)					
0.66	*Anisoptera curtisii*	Keruing	Fs	0.62 (0.07–2.3)					
0.65	*Swietenia mahagoni*	Mahoni	Ps		0.24		0.21		
0.65	*Calliandra calothyrsus*	Anjra/kaliandra	Ps	0.16 (0.06–0.27)					
0.64	*Bischofia javanica*	Gintungan	Fs	0.3					
0.64	*Crescentia cujete*	Mojo	Fs	0.26 (0.06–0.63)					
0.64	*Leucaena leucocephala*	Lamtoro	Vs			0.46 (0.16–2.3)	0.27 (0.12–0.53)	0.46 (0.10–1.53)	
0.63	*Coffea canephora*	Kopi	Ps			0.33 (0.10–3.22)	0.13 (0.04–0.56)	0.19 (0.08–0.36)	0.18 (0.06–0.28)
0.63	*Bambusa* spp.	Bambu	Fs, Vs	0.12 (0.06–0.21)	0.15 (0.05–0.25)				
0.63	*Syzygium polyanthum*	Salam batu	Fs	0.57 (0.16–1.53)					
0.62	*Breynia microphylla*	Berasan	Fs	0.19					
0.61	*Tectona grandis*	Jati	Ps					0.41 (0.07–0.14)	
0.61	*Angiopteris evecta*	Pakis gajah	Fs	0.74 (0.65–0.84)					
0.61	*Microcos tomentosa*	Trete	Fs	0.29 (0.12–0.61)					
0.60	*Mangifera indica*	Mangga	Ps			0.38	0.11		
0.57	*Ficus variegata*	Godangan	Fs	0.93	0.68 (0.25–1.01)				
0.56	*Durio zibethinus*	Durian	Fs, Vs, Ps		0.31 (0.08–0.48)	0.74 (0.17–1.84)	0.32 (0.04–1.33)		0.41 (0.11–0.60)

Table 2 (continued)

WD, g cm^{-3}	Scientific name	Local name	Group	Measurement: mean BA across all plots, m^2 ha^{-1} (value range)					
				Remnant forest		Complex agroforestry		Simple agroforestry	
				2007	2017	2007	2017	2007	2017
0.56	*Persea americana*	Alpukat	Vs			1.09 (0.14–2.24)		0.74	0.68
0.53	*Artocarpus heterophyllus*	Nangka	Ps			2.22 (1.08–2.24)	1.11		1.11 (0.37–1.87)
0.50	*Ficus benjamina*	Beringin	Fs	0.1	1.92 (0.21–3.29)				
0.50	*Cocos nucifera*	Kelapa	Ps			0.39 (0.36–0.41)	0.06 (0.05–0.06)		
0.48	*Macaranga tanarius*	Tutup	Fs	1.01 (0.86–1.15)	0.66 (0.24–2.14)				
0.48	*Basella alba*	Lembayung	Ps		1.24		1.08		
0.48	*Parkia speciosa*	Petai	Ps				0.17		0.35 (0.105–0.49)
0.48	*Hibiscus* sp.	Waru	Fs, Vs	1.05	0.54 (0.12–1.33)	0.34 (0.1–0.52)	0.48 (0.06–1.11)		
0.47	*Engelhardtia spicata*	Kukrup	Fs	1.01 (0.73–2.49)	0.9 (0.05–1.75)				
0.47	*Prunus arborea*	Nyampo	Vs		0.39 (0.35–0.43)	0.43 (0.37–0.52)	0.31 (0.07–0.76)		
0.45	*Maesopsis eminii*	Masusi	Vs				0.46		
0.42	*Theobroma cacao*	Kakao	Ps			0.3			
0.41	*Anthocephalus cadamba*	Jabon	Fs		0.49 (0.19–0.78)		1.28		0.23
0.40	*Toona sureni*	Surian	Ps	2.7 (1.98–3.37)	0.73 (0.35–1.27)		0.48 (0.11–1.08)		
0.36	*Trema orientalis*	Anggrung	Fs, Ps	0.67	0.68				
0.35	*Parasponia rigida*	Anggrung hijau	Fs, Vs, Ps	0.67			0.28 (0.09–0.44)		
0.33	*Hernandia nymphaeifolia*	Jambu hutan	Fs		0.61 (0.38–0.89)				
0.33	*Falcataria moluccana*	Sengon	Vs						0.25 (0.04–0.65)
0.32	*Laportea stimulans*	Kemado	Fs	0.3	0.21 (0.05–0.12)				
0.32	*Erythrina indica*	Dadap	Vs, Ps			0.8 (0.54–1.15)	0.6		0.55 (0.36–0.71)
0.13	*Carica papaya*	Pepaya	Ps				0.26		
0.03	*Musa* spp.	Pisang	Ps			1.02 (0.12–3.22)	0.61 (0.20–1.61)	0.47 (0.16–0.71)	0.63 (0.17–1.57)

AF agroforestry systems, *BA* basal area, *Fs* forest species, *Vs* voluntary/tolerated species, *Ps* planted species

death (Wilson et al. 2015). Reactive forms of sulphur and other hazardous substances in volcanic ash can cause acid damage, generating a burning effect that harms the leaves and stems. In coffee-based agroforestry systems, the disruption level of tree species decreased with increasing WD. This indicates that slow-growing tree species were less affected,

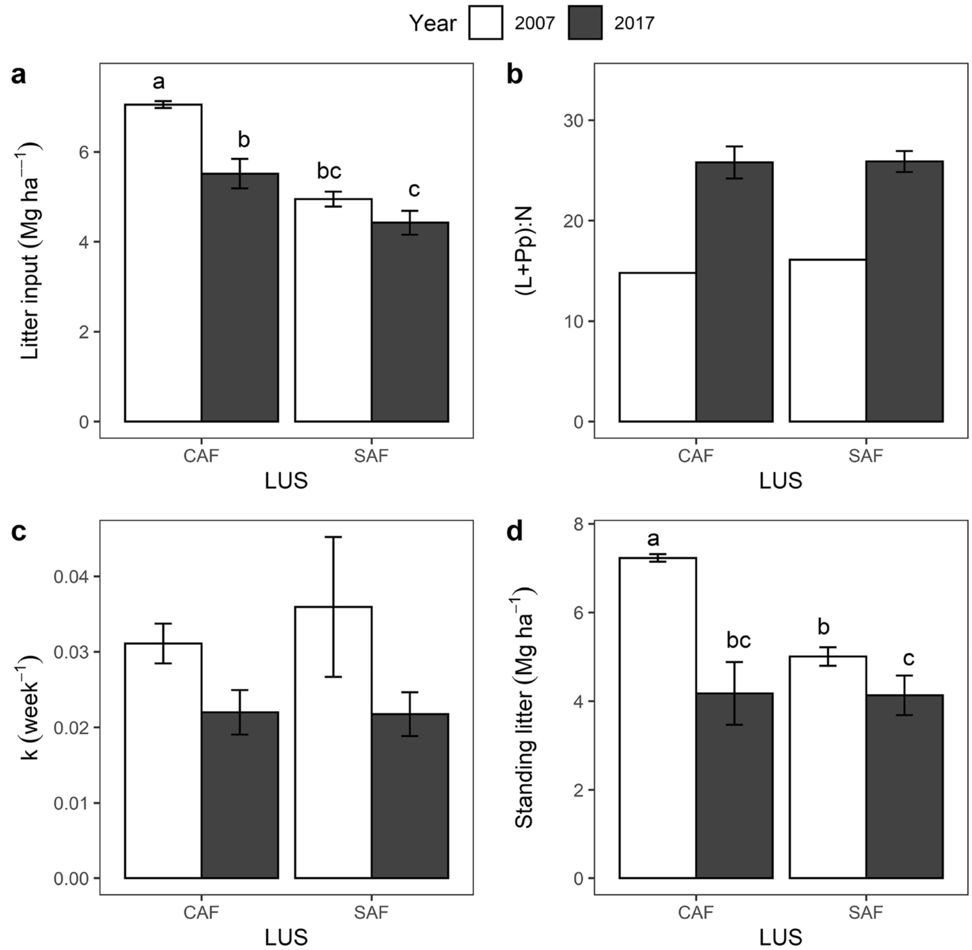

Fig. 4 **a** Annual litter input, **b** litter quality ((L + P):N), **c** decomposition rate (k), and **d** standing litter stocks of coffee-based agroforestry systems in 2007 and 2017 (*CAF* complex agroforestry systems, *SAF* simple agroforestry systems, *LUS* land-use systems; different letters indicate a significance difference ($P < 0.05$) when there was a significant interaction between LUS and year)

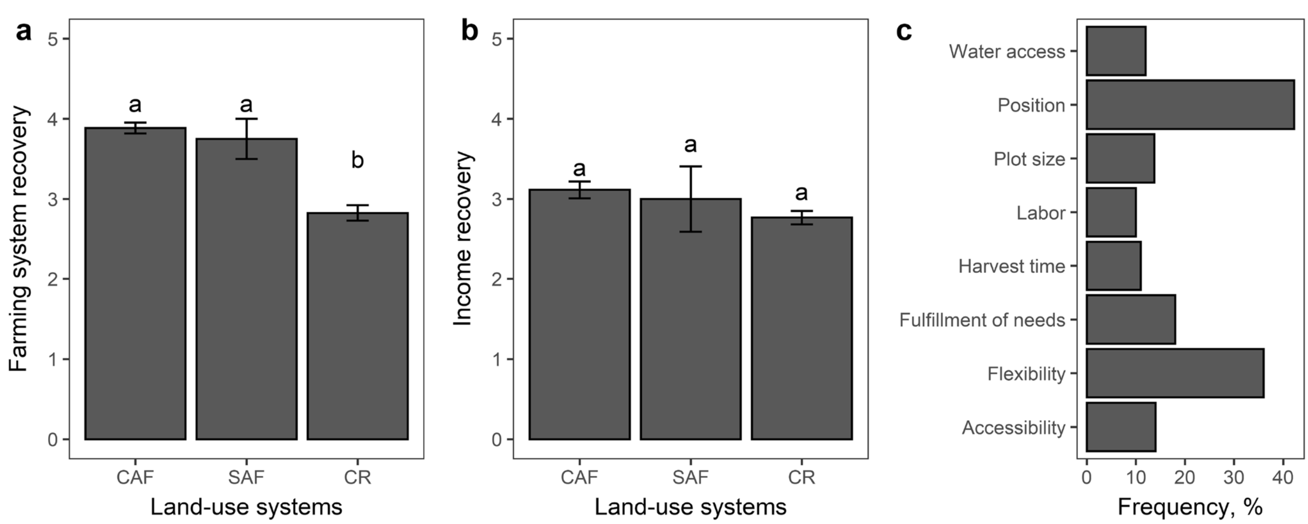

Fig. 5 Farmer's perspective on the capacity of different land-use systems to recover from the volcanic eruption ($n = 46$). **a** Farming system recovery; **b** income recovery; and **c** reasons for choosing a land-use system

in agreement with results of Greenwood et al. (2017), who reported that tree species with denser wood showed lower mortality responses to drought. In our study, most of the high WD tree species retained at least half of their leaves with less branch damage compared to other tree species. High wood density species are probably less likely to be

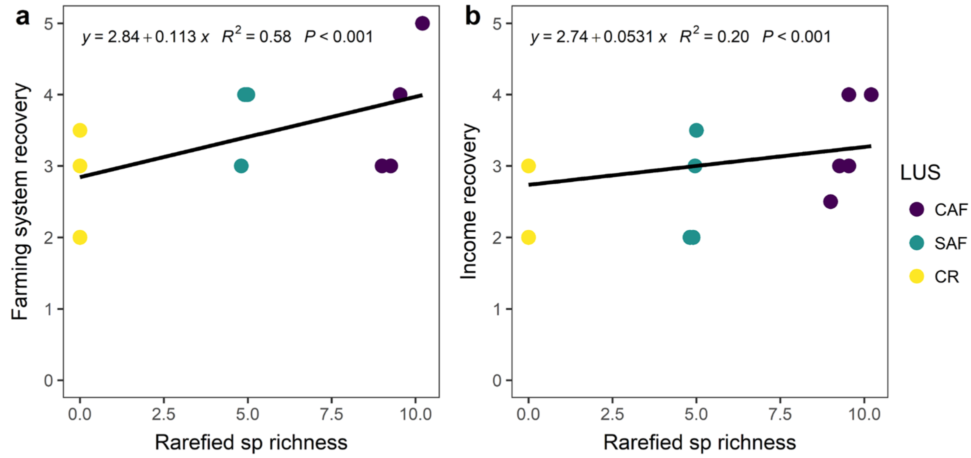

Fig. 6 Relationship between rarefied species richness (number of species per 40 stems) and **a** farming system recovery, and **b** income recovery, based on farmer interviews (score 1 = very low; 2 = low; 3 = moderate; 4 = high; 5 = very high; *LUS* land-use system, *CAF* complex agroforestry system, *SAF* simple agroforestry system, *CR* crops system)

damaged by ash deposition on leaves and branches. High wood density trees can carry heavier loads with less damage to branches (Niklas 2016; Niklas and Spatz 2010). High wood density trees also have tougher leaves (Alvarez-Clare and Kitajima 2007), which might reduce the abrasive effect that ash can have (Black and Mack 1984). We discovered that the severity of disruption was positively associated with the time to recover, which was also found in other studies on forest disturbance (Bartels et al. 2016; Dale et al. 2005; Franklin et al. 2002).

The effect of the volcanic eruption on aboveground C stocks, diversity and WD

To assess the effect of the Mt. Kelud eruption, we determined the aboveground C stocks, tree diversity, tree species composition, and mean WD across the land-use gradient before and 3 years after the event. We, unexpectedly, found that the aboveground C stocks remained the same after the volcanic eruption, while tree diversity and the WD range increased. One reason for this could be that deposition of < 15 cm volcanic ash would just damage aboveground plant parts, and not result in tree mortality (Eggler 1963; Rees 1979). Another reason could be that farmers adapted the systems by planting trees after the eruption. The significant increases in tree diversity and the WD range in coffee-based agroforestry systems after the disturbance suggest that farmers actively responded to the eruption by (trans)planting trees, including *P. rigida* and *D. zibethinus* to replace dead trees. Farmers transplanted *P. rigida* wildings they found germinating in volcanic ash deposits along rivers; this species performs well on low-nitrogen ash soils by producing root nodules with rhizobium bacteria (Dupin et al. 2019; Trinick and Hadobas 1989); it may support the recovery process as it produces high-quality litter, which increases soil organic matter and soil nutrient content (Ishaq et al. 2020a), as well as usable timber. In contrast, tree diversity in the remnant forest did not change in response to volcanic ash deposition. However, the number of pioneer trees in RF, such as *Macaranga tanarius*, increased in most of the plots (Table 2), indicating that RF was disturbed or damaged by volcanic ash deposition.

Low litter quality in coffee-based agroforestry compensated for low litter input after a volcanic eruption

We expected the litter input in coffee-based agroforestry systems to decrease after volcanic ash deposition, with lower litter quality slowing down the decomposition rate, decreasing the standing litter stocks of coffee-based agroforestry systems. Although the volcanic eruption did not significantly affect the aboveground structure, litter dynamics were significantly affected. Since we did not find a significant change in BA, the considerably lower litter input in coffee-based agroforestry system after the volcanic eruption probably resulted from (1) a shift towards high WD that was found in SAF (Fig. 3e); (2) the effect of volcanic ash deposits that might weaken trees by damaging their leaves directly by leaching cations and damaging cuticles and, indirectly, limiting the nutrients available to them, altering photosynthesis and plant growth (Carlón Allende et al. 2019; Gu et al. 2003; Tognetti et al. 2012); (3) the adverse effect of ash deposition which decreased soil aggregate stability and limited soil infiltration (Saputra et al. 2022), which may suppress tree and foliage re-growth (Carlón Allende et al. 2019; Segura et al. 1995; Wilson et al. 2011); and/or (4) increased shade tree pruning for fodder use after the eruption (Kusumawati et al. 2022).

We also found that litter in coffee-based agroforestry systems decomposed more slowly after the volcanic eruption. This result is in line with results of Purnamasari et al. (2021), who found that fine tree roots in the same sites decomposed slower on topsoil with recent volcanic ash. Similarly, volcanic ash deposition decreased composition rates in *Nothofagus dombeyi* forests of NW Patagonia (Piazza et al. 2018). However, faster decomposition in response to ash deposition was found in a simple coffee-based agroforestry system in Indonesia (Ishaq et al. 2020b). In our study, modification of tree species composition in the agroforestry systems after the eruption, as indicated by a higher range of WD in SAF (Fig. 3e), may have increased litter (L + Pp):N content, and decreased litter decomposition rates with 35% (Fig. 4c). In addition, low decomposition rates after the eruption may be due to effects of ash deposition on soil processes. Volcanic ash forms an organo-mineral complex with organic matter in the soil that physically protects organic matter from decomposition as it becomes inaccessible to decomposers (Dahlgren et al. 2004). Volcanic ash mixed with organic matter becomes hydrophobic, which decreases water infiltration in the soil (Saputra et al. 2022, 2023). Therefore, drought stress after volcanic ash deposition could reduce decomposer activity and growth, and decelerate organic matter decomposition.

Low litter input and the lower decomposition rate after the eruption resulted in a 30% decrease of standing litter stocks. This result agrees with results of Saputra et al. (2022), who found a 10–50% decrease in standing litter stocks in the same site 3 years after the eruption. However, the low litter quality in the coffee-based agroforestry systems may have compensated for the low litter input after volcanic ash deposition, maintaining the litter layer function to protect the soil surface from the direct impact of rainfall and solar radiation.

Social–ecological resilience of the systems in response to the volcanic eruption

While most tree species in the agroforestry system survived, most crops were (partially) buried by ash and died. From the farmers' perspective, annual crop systems had lower ecological resilience than agroforestry systems, but financial resilience did not differ between the systems. The similar income recovery of annual crop systems 3 years after the eruption could be due to the high amount of fertilizer input (twice as much as in coffee-based agroforestry systems) and intensive soil management, which support crop growth. Saputra et al. (2022) indicated that soil organic C in annual crop systems in this area tended to increase after the eruption, not because of a positive impact of volcanic ash addition, but due to high organic fertilizer input. The associated production cost in crop systems, however, might also rise because of increased fertilizer input and associated labour costs. Volcanic ash deposition did not increase soil C organic content in the short term and could even inhibit plant growth through the encrusted ash layer which decreases water infiltration and soil aggregate stability if it is not removed (Saputra et al. 2022). In the long term, a positive effect of volcanic ash on soil fertility is expected. The need for intensive management, i.e., mixing ash and soil, before being able to replant annual crops, indicated that the crop system was more vulnerable to volcanic ash deposition. Although there was statistically no difference in income recovery between agroforestry systems and annual crop systems 3 years after the eruption, the income of annual crop farmers fluctuated more during that period. Thus, if the production and labour cost are also included in the calculation of the income (using "net income" instead of "total income"), income may be higher in agroforestry systems, since the production and maintenance costs for crop systems were higher than for coffee-based agroforestry systems. However, none of the crop farmers decided to plant trees in crop systems directly after the eruption. Still, they modified their crop species, by planting, for example, Napier grass and maize for fodder instead of rice or cabbage to avoid harvest failure. Agroforestry systems had more options for generating income because of their high diversity. After the eruption of Mt. Merapi in 2010 in Central Java, Indonesia, agroforestry farmers could generate 58–90% of their total income from the system still (Rahman et al. 2016; Rozaki et al. 2021b). The higher resilience of agroforestry systems probably resulted from (1) the lower impact of volcanic ash deposition on the system (Rozaki et al. 2021a), (2) the higher diversity that supports system stability (Perfecto et al. 2019), (3) the faster recovery after the disturbance, and (4) the management response of farmers after ash deposition. Species diversity in agroforestry systems is essential as a buffer against environmental fluctuations, enhancing the ecosystem's stability (Hutchison et al. 2018; McCann 2000). Our findings provide empirical evidence for the idea that tree diversity in agroforestry systems enhances social–ecological resilience. Similarly, higher diversity in agroforestry systems in Kenya was found to enhance livelihood resilience in Kenya (Quandt et al. 2018).

Farmers have the ability (agility) to adapt to changes by optimizing the flexibility of agroforestry systems to accommodate all possible opportunities to fulfil daily needs and enhance economic benefit. It supports the sustainagility concept proposed by Jackson et al. (2010) and van Noordwijk (2010), where the characteristics of a system can support an agent's capacity (agility) to adapt and satisfy their needs in new ways in the face of unexpected circumstances. As rapid vegetation recovery is desirable for farmers to secure income, most planted trees that perform well in agroforestry systems had a stable production (de Foresta et al. 2004). We found that after the volcanic eruption, ash-tolerant shade tree species with high economic value, such as durian and timber species such as *Hibiscus* sp. (Table 2) were planted more frequently. The presence of more legume tree species in coffee-based agroforestry after the eruption may also be related to the increase in fodder demand in this area, as the importance of livestock gradually increased (Lusiana et al.

2012). Thus, agroforestry farmers tried to diversify their income to minimize the negative effect of unexpected external shocks on their livelihood in the future. If, and in what way, farmers diversify their systems to enhance resilience depends on the choices that farmers make. In Cameroon, for instance, smallholder farmers designed their systems as such to enhance resilience to climate variability and change, mainly relying on past experience of extreme weather/climate events, which influenced by their socio-economic situations, such as household income, size, gender, and age, including membership in farmer group and access to credit and market (Awazi et al. 2019).

Active, adaptive farmer management in response to a volcanic eruption is essential to stimulate ecological and financial recovery of coffee-based agroforestry systems from volcanic eruptions. Increasing species diversity in coffee-based agroforestry systems seems beneficial for increasing recovery rates, thus the resilience of the system, by enhancing their capacity to withstand disturbances without significantly changing system structure and retaining the provision of environmental services, such as carbon storage and income provision (Luck et al. 2003; Silva Pedro et al. 2015). Although the agroforestry system can absorb the negative impact of sudden shocks through its flexibility and diversity, proper management responses, including tree recruitment, will determine the resilience of the social–ecological system. Our results, thus the enhanced understanding of system dynamics in response to a disturbance, are essential in preventing severe impacts of future disturbances. With the recent prediction of a more frequent eruption cycle of Mt. Kelud in the future (Indriyanto et al. 2023; Maeno et al. 2019a), the agility of smallholder farmers needs to be enhanced and synchronized with government policies to help accelerate system and livelihood recovery in the future.

Conclusions

In this study, we had the unique opportunity to evaluate the resilience of coffee-based agroforestry systems in response to volcanic ash deposition during the Mt. Kelud eruption in 2014 in East Java, Indonesia, to provide an empirical test of the hypothesis that diversity enhances the (social–ecological) resilience to disturbance. We found that the volcanic eruption, which precipitated up to 15 cm ash, immediately affected annual crops and low WD tree species in agroforestry systems. However, aboveground structure and C stocks in coffee-based agroforestry systems and the remnant forests were not significantly affected, because most trees survived. While the effect of ash deposition on litter dynamics in coffee-agroforestry systems was noticeable, the change in litter input and decomposition was found to be balanced. Thus, litter layer functions were maintained after the disturbance. Farmers adapted the systems in response to the volcanic eruption, as tree species diversity increased in response to the disturbance. This adaptive response determines to what extent the system can retain its basic functions and recover from disturbance. Enriching tree diversity may enhance the resilience of coffee-based agroforestry systems by increasing their buffering capacity against external shocks, which may increase food and income security.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11625-023-01400-6.

Acknowledgements This study was supported by the Tropical Agroforestry Research group, Brawijaya University, Indonesia and the Directorate General of Resources for Science, Technology and Higher Education of the Republic of Indonesia. The authors would like to thank the farmers in Tulungrejo and Sumberagung Village, Ngantang sub-district, East Java, Indonesia, for their long-term commitment, kind help and support, and a warm family welcome. Many thanks to the research assistant team: Rizky Maulana Ishaq, Eka Purnamasari, Anggi Eka Putri, and Fatchuliani S. Ramadhani for the field assistance and laboratory work.

Author contributions All authors contributed to the study concept and design. Material preparation, data collection and analysis were performed by RRS, RP, DDS and DMAR. The first draft of the manuscript was written by RRS and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding We acknowledge financial support from Brawijaya University, Indonesia, through the Junior staff research grant (Hibah Peneliti Pemula) and Featured research grant (Penelitian Unggulan Perguruan Tinggi) for the 2016/2017 fieldwork. The Ministry of Research and Technology provided financial support for the 2007/2008 fieldwork through the HIRD Project and Doctoral grants.

Declarations

Conflict of interest No competing interests to declare by the authors.

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