**BIODIVERSITAS**
Volume 25, Number 10, October 2024
Pages: 3412-3422

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d251003

# Discovering potential forage species under *Acacia decurrens*-based silvopastoral system in different elevations of post-eruption recovery in Mount Merapi, Indonesia

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Manuscript received: 26 July 2024. Revision accepted: 3 October 2024.

**Abstract.** *Mursyid H, Faridah E, Maulana H, Silmia B, Suryanto P. 2024. Discovering potential forage species under* Acacia decurrens-*based silvopastoral system in different elevations of post-eruption recovery in Mount Merapi, Indonesia. Biodiversitas 25: 3412-3422.* The devastating eruption of Mount Merapi, Indonesia, in 2010 resulted in the alteration of vegetation composition and structure across the exposed area, and it has been invaded by *Acacia decurrens* Willd. ever since. Nevertheless, *A. decurrens* provides a suitable agroecosystem for silvopasture, which has been considered the essential source of income for the society around Merapi. This research aims to observe the diversity and potential forage species under silvopastoral systems in different elevations. The study was conducted in three villages located at different elevations *viz.* Kalikuning (820 masl), Kaligendol (890 masl), and Balerante (1,100 masl). There were 15 research plots for vegetation survey built in each location based on purposive sampling. A nested design (20 m × 20 m), comprised of 5 subplots, was employed to observe the distribution of *A. decurrens* and understory species. The study observed that *A. decurrens* was the only shade tree in all locations. The average of *A. decurrens* in all growth stages for each location ranges from individuals ha$^{-1}$. There were 33 understory species of 13 families observed in all locations. The highest number of understory species was observed in Kaligendol (20 species), followed by Kalikuning (16 species) and Balerante (10 species). Similarly, Kaligendol showed the highest species richness (Dmg = 3.16). However, the highest heterogeneity (H' = 1.98) and evenness (J' = 0.71) was recorded in Kalikuning. There were 61% and 9% of understory species classified as palatable and unpalatable, respectively. Stand management, such as enrichment planting and regular pruning, is required to maintain the sustainability and productivity of silvopasture in the post-eruption areas.

**Keywords:** Merapi eruption, plant biodiversity, potential forage, silvopasture

## INTRODUCTION

Mount Merapi is one of the most active volcanoes in Indonesia. There have been 70 eruptions recorded since 1948 (Voight et al. 2000). In 2010, the vast area was exposed to detrimental damage due to Merapi eruption. The eruption emitted volcanic materials ranging from 1.5-5 million km$^3$, forcing 350,000 residents to evacuate their homes (Jenkins et al. 2016). Besides, native vegetation species in close proximity to the eruption area, especially in forests on the southern, western, and northern slopes of Mount Merapi, were also severely damaged. However, this damage played a crucial role in promoting primary succession across the area, a key step in the recovery process. This happened because the hot cloud slide reached up to 14 km from the peak of the eruption. The most predominant species observed in the aftermath was *Acacia decurrens* Willd. It was initially introduced by *Perhutani* (Indonesian Forestry Public Company) for its benefits, such as charcoal or *batik* material extracted from its bark (Ferede et al. 2019). However, the adaptability of *A. decurrens* to extreme heat and fast-growing habits inevitably led to its invasiveness (Suryawan 2015; Afrianto et al. 2017) and eventually threatened the diversity in the exposed area. The *A. decurrens* replaced *Erythrina* spp. and *Pinus merkusii* Jungh. & de Vriese as the native species preceding the eruption (Sunardi et al. 2017). Invasive species can jeopardize the survival of native species, the plant composition and structure within the ecosystem, and socio-economic of the society (Richardson et al. 2015). Despite its threat to ecological diversity, *A. decurrens*, which is typically characterized by its low crown density, contributes to adequate light availability for understory vegetation. It provides a suitable agroecosystem for silvopasture, which has been introduced as sustainable livestock management by supplying an excellent source of fodder for the farmers. The *A. decurrens* has been acknowledged for its high economic benefits and ecosystem services in degraded areas in Ethiopia (Chanie and Abewa 2021; Nigussie et al. 2021; Debie and Anteneh 2022).

There are multiple benefits offered by silvopasture, such as increasing land productivity, higher livestock performance, optimizing resource utilization, including sustainable livestock management (Jose and Dollinger 2019). Successful silvopastoral management relies on several principles proposed by Jose et al. (2019), *viz.*

maximizing resource use efficiency based on spatial and temporal heterogeneity, alleviating resource competition among perennial components within the system, maintaining structural and functional diversity for resource conservation, and integrating the perturbance principle into the silvopastoral design. The high possibility of resource competition among components within silvopasture urges comprehensive design and integrated land management to ensure the sustainability of the system. The understory plants require adequate light availability to grow optimally and to maintain their diversity (Guenni et al. 2018; Dormann et al. 2020). Therefore, tree species selection should consider its crown type and inhibitory traits (e.g., allelopathy effect), including stand management. A previous study about herbage accumulation of *Brachiaria brizantha* (A.Rich.) Stapf under *Eucalyptus urograndis*-based silvopasture observed that moderate shading (4-m distance from the edge row of *E. urograndis*) could maintain productivity by enhancing *B. brizantha* leaf area and decreasing tiller density (Nascimento et al. 2021). To minimize potential negative impacts and ensure that the different components of the system coexist harmoniously, careful species selection and management practices are essential. This includes not only choosing appropriate tree species and managing their growth but also considering the potential invasiveness of certain plants. For instance, the invasiveness of *A. decurrens* is believed to disrupt the productivity and sustainability of silvopasture in the exposed area (Haryadi et al. 2019).

Silvopasture has been an important source of income for the society in several villages surrounding the Merapi. To date, silvopasture research focusing on post-eruption area is limited to *Falcataria moluccana* (Miq.) Barneby & J.W.Grimes- based silvopasture (Dewi et al. 2020; Suwignyo et al. 2022) and signalgrass (*B. brizantha*) silvopasture (Suryanto et al. 2020), in different observation areas. Other related publications discussed understory plant composition in different exposed areas (Pasaribu et al. 2021) and the identification of its benefit for fodder, medicinal purposes, or fertilizer (Suharti 2015). Plant composition encountered in different elevations can represent the potential fodder source in each location. Plant species, as well as fodder species, varied at different elevations; plant diversity and composition decline with elevations (Lee et al. 2021; Mauki et al. 2023).

This study aims to identify the diversity of understory species and their potential benefit to promote sustainable silvopastoral systems in three eruption-exposed areas (Kaligendol, Kalikuning, and Balerante) located in different elevations. Silvopasture has been reckoned as an essential source of income for the society in these locations. Therefore, observation and further identification of potential forage species, especially under *A. decurrens* stand, are essential as references for further *A. decurrens*-based silvopasture research or management in the post-eruption area.

## MATERIALS AND METHODS

### Study area

The research was conducted in the South Mount Merapi slope area located in Yogyakarta, Indonesia (7°32'28.18"S - 7°39'16.578"S and 110°25'34.92"E - 110°28'17.35"E) (Figure 1). The research covered three villages *viz.* Kalikuning, Kaligendol and Balerante located on 820, 890, 1,100 masl, respectively. Annual rainfall is recorded at 875-2,527 mm year$^{-1}$. The temperature and annual average range were 20°C-30°C and 23°C, respectively, with climate type C according to Schmidt and Ferguson classification. Mount Merapi last erupted in 2010, causing various levels of damage. These locations experienced serious damage, leading to primary succession, which in turn replaced native vegetation (Utami et al. 2021). Volcanic materials, predominantly 85% gravel, 10% sand, and 5% ash, were observed on the soil surface in these locations.

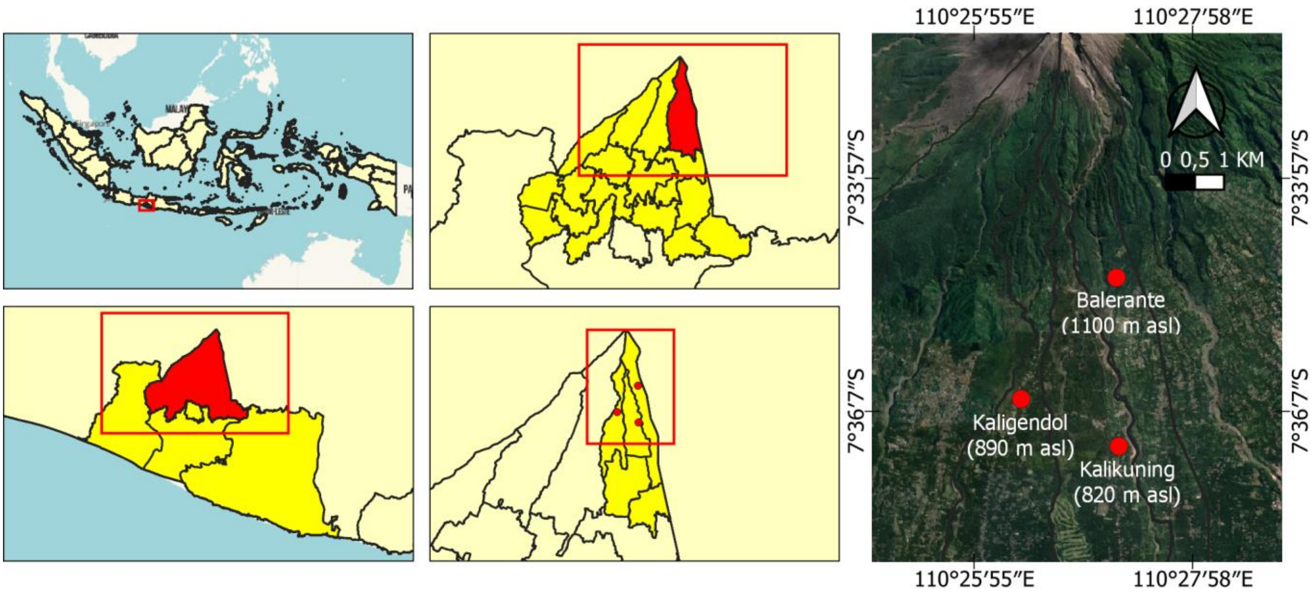


**Figure 1.** Study area in three different elevations: Kalikuning (820 m asl), Kaligendol (890 m asl), and Balerante (1100 m asl)

**Table 1.** Soil characteristics of each research location

| Characteristics | Unit | Kalikuning | Kaligendol | Balerante |
|---|---|---|---|---|
| Cation Exchange Capacity (CEC) | cmol | 13.32$^{L}$ | 12.5$^{L}$ | 15.89$^{L}$ |
| Base saturity | % | 7.78$^{VL}$ | 8.66$^{VL}$ | 7.51$^{VL}$ |
| pH $H_2O$ | - | 6.53$^{SA}$ | 6$^{SA}$ | 6.48$^{SA}$ |
| Organic C | % | 1.97$^{L}$ | 1.84$^{L}$ | 1.73$^{L}$ |
| Total N (%) | % | 0.19$^{L}$ | 0.14$^{L}$ | 0.04$^{VL}$ |
| Soil available K (ppm) | ppm | 19$^{L}$ | 22$^{L}$ | 12$^{L}$ |
| $P_2O_5$ (ppm) | ppm | 29$^{M}$ | 34$^{M}$ | 22$^{M}$ |
| Ca-dd (cmol/kg) | cmol $kg^{-1}$ | 0.76 | 0.83 | 0.96 |
| Mg-dd (cmol/kg) | cmol $kg^{-1}$ | 0.19$^{L}$ | 0.18$^{L}$ | 0.15$^{L}$ |
| K-dd (cmol/kg) | cmol $kg^{-1}$ | 0.05$^{L}$ | 0.06$^{L}$ | 0.03$^{L}$ |
| Na-dd (cmol/kg) | cmol $kg^{-1}$ | 0.02 | 0.02 | 0.03 |

Note: SA: Slightly Acid; VL: Very Low; L: Low; M: Moderate; classification was based on United States Department of Agriculture (1999)

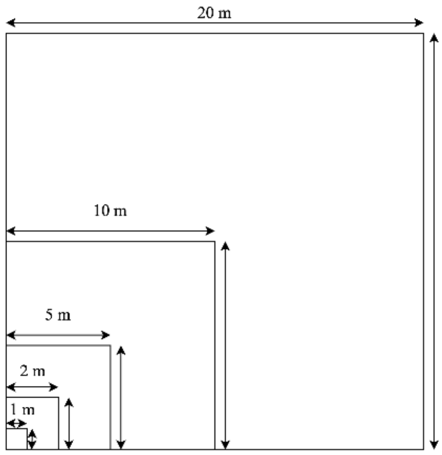


**Figure 2.** Nested plot for vegetation survey

## Soil characteristics

All locations in this study were exposed severely to the eruption resulting in the formation of alluvial soil. Soil analysis was conducted to determine the soil chemical characteristics in each location. Despite showing various values, almost all soil chemical characteristics in each location were classified at similar levels. It can be inferred that almost all soil chemical characteristics in each location were classified as low, except for Phosphorus content, which was classified as moderate. Besides, the pH in all locations was slightly acidic. Soil chemical characteristics recorded in Balerante were mostly the lowest compared to other locations, particularly in base saturity, organic C, total N, soil available K, P content, exchangeable Mg (Mg-dd), and K (K-dd) (Table 1) (Unpublished data).

## Procedures

The study was conducted from August - October 2017. Vegetation composition in each location was observed based on purposive sampling consisting of 15 plots, which were evenly distributed in each location. Nested plots were established for vegetation survey, which were composed of different subplots for each growth stage *viz*. 1 m x1 m for understory, 2 m x 2 m for seedlings at 5 m x 5 m for saplings, 10 m x10 m for poles and 20 m x 20 m for trees (Figure 2). The definition of growth stages refers to Soendjoto et al. (2014). Parameters observed for understory species were species, number of species, and palatability of each species. Total individuals of *A. decurrens* at different growth stages (seedling, sapling, pole, and tree) were observed to determine their distribution in all locations.

## Data analysis

There were 6 indicators calculated for Importance Value Index (IVI) analysis, which were species density, species dominance, species frequency, relative density, relative dominance, and relative density (Zayadi et al. 2024). IVI analysis was only performed for understory species because *A. decurrens* was solely shade-tree observed in all locations. Diversity indicators analyzed in this study were calculated as follows:

$$\text{Species density} = \frac{\textit{Number of individual}}{\textit{Size of sampling plot}}$$

$$\text{Species dominance} = \frac{\textit{Total basal area of spesies}}{\textit{Size of sampling plot}}$$

$$\text{Species frequency} = \frac{\textit{Number of plot wherein species existing}}{\textit{Total sampling plot}}$$

$$\text{Relative density} = \frac{\textit{Relative density}}{\textit{Total species density}} x100$$

$$\text{Relative dominance} = \frac{\textit{Species dominance}}{\textit{Total species dominance}} x100$$

$$\text{Relative frequency} = \frac{\textit{Species frequency}}{\textit{Total species frequency}} x100$$

Important Value Index = Relative density + Relative dominance + Relative frequency

Vegetation diversity indices were quantified based on the Margalef index to represent species richness (Dmg), the Shannon Winner Index (H') to represent species heterogeneity (Li et al. 2018), and the Pielou-Evenness Index (J') to represent species evenness (Wirabuana et al. 2021). Besides, the Similarity Index (SC) was also measured to determine the resemblance of understory plant composition among observed locations in terms of shared species. The equations of those parameters are presented below:

$$\text{Dmg} = \frac{S-1}{\ln(N)}$$

$$\text{H'} = \sum\left(\frac{n_i}{N} \times \ln\frac{n_i}{N}\right)$$

$$\text{J'} = \frac{H'}{\ln(S)}$$

$$\text{SC} = \frac{2W}{(A+B)}$$

Where:
S : Number of species
N : Total number of individuals in each location
$n_i$ : Number of individuals in each species
W : Number of shared species discovered in all locations
A, B: Number of species discovered only in specific locations.

Statistical analysis was performed using Microsoft Excel and RStudio version 2024.04.2+764.

## RESULTS AND DISCUSSION

### Distribution of *Acacia decurrens* and understory species

Primary succession occurred after the devastating Mount Merapi eruption in 2010, resulting in the alteration of species composition. Native vegetation in the exposed areas was replaced by *A. decurrens,* which eventually became an invasive species (Setyawati et al. 2015). Nevertheless, it provides a suitable agroecosystem for understory species, which were mostly harvested as fodder. Silvopasture has been reckoned as the pivotal source of income for several villages around Merapi, including Kalikuning, Kaligendol, and Balerante. Most foraging activities are conducted in Balerante because of limited access to Kalikuning and Kaligendol, as these locations are under the jurisdiction of Merapi National Park. The only shade tree observed in all locations was *A. decurrens*. On average, there were 271 individuals/ha discovered in three research locations for almost all growth stages. Total seedlings discovered in Kalikuning and Balerante were identical, whereas seedling was not discovered in Kaligendol (Figure 3). The number of saplings recorded in Balerante was abundant and five times higher than that of other locations. Balerante also showed the highest number of poles but a lower number of trees compared to Kaligendol. The absence of seedlings in Kaligendol could be related to the lack of land management contributes to the lack of mechanical treatment of the seeds, which inhibits its germination. The *A. decurrens* is known for its orthodox-type seed, identical to other Fabaceae. Consequently, pre-treatments such as extreme heat or mechanical treatment to its skin through land mowing are required to induce seed germination (Richardson et al. 2015; Lieurance et al. 2024).

Stand composition and density within the silvopasture system can contribute to the diversity and growth of understory species. The vegetation structure of *A. decurrens* was varied in all locations. Higher diversity and abundance of understory species in Kalikuning might be associated with lower tree density compared to other locations resulting in lower resource competition and higher light availability to the forest floor. Moderate tree density (≤500 trees $ha^{-1}$) provided higher herbage mass and nutritive value of Massai grass (*Megathyrsus maximus* (Jacq.) B.K.Simon & S.W.L.Jacobs) combined with leguminous trees (*Dalbergia retusa* Hemsl., *Platymiscium pinnatum* (Jacq.) Dugand, and *Diphysa americana* (Mill.) M.Sousa) and non-leguminous trees (*Swietenia macrophylla* G.King) (Dibala et al. 2021).

Distribution of *A. decurrens* in the exposed area can be associated with soil acidity. Ashfall caused by the eruption can lead to decreasing soil pH due to high sulphur levels, which eventually promotes nutrient imbalance (Baillie et al. 2018). Low phosphorus content mostly occurs in low soil pH due to lower phosphorus retention (17.5%-43.4%) (Anda et al. 2023). In the post-eruption areas, the reactive surface of allophanes and humus-Al complexes can bind phosphorus, resulting in chemical compounds unavailable to plants (Mihai et al. 2023). Higher pH in Balerante and Kalikuning might be attributed to higher *A. decurrens* density, especially saplings, compared to that of Kaligendol, although the soil in all locations was classified as slightly acidic (Table 1). The number of saplings in Balerante is the highest because most trees were harvested for charcoal, resulting in the robust growth of the younger *A. decurrens.* On the contrary, *A. decurrens* in Kalikuning and Kaligendol were not harvested because these locations are under the jurisdiction of Mount Merapi National Park; hence, the society avoided the conflict. Vegetation density can promote physicochemical changes in soil due to litterfall. Besides, all parts of harvested *A. decurrens,* except for its bark and trunk, were left on the surface of the soil as mulch, which can contribute to the improvement of soil properties in the long term. Similarly, Amare et al. (2022) reported remediation of acid soil in *A. decurrens*-based crop-livestock system in the Ethiopian highlands. Another report on changing soil pH in regard to vegetation density discovered that increasing pH was reported in locations with higher tree density than moderate tree density (Tokozwayo et al. 2021).

There were 33 understory species from 13 families identified in all locations (Table 2). Most species were observed in Kaligendol (20 species), followed by Kalikuning (16 species) and Balerante (11 species). Different species composition in these locations might also be attributed to the thicker alluvial layer on the soil surface in Kaligendol (7%) compared to other locations (3%) (unpublished data). Alluvial soil is formed from materials deposition, such as sand, mud, or gravel, through river flow to lower area (Miller and Juilleret 2020). Different soil layers contribute to distinctive soil physical and chemical characteristics, which subsequently promote particular species composition in each location (Saint-Laurent and Arsenault-Boucher 2020).

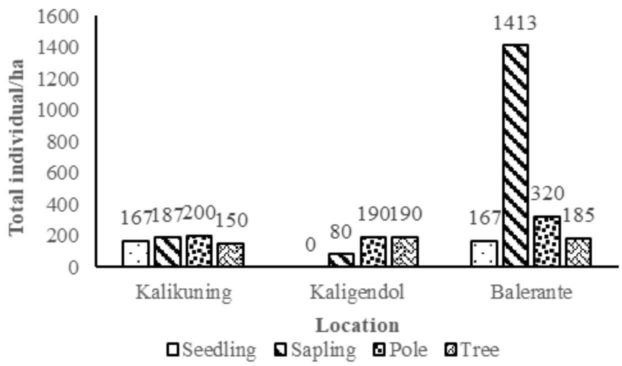


**Figure 3.** Total individuals of *Acacia decurrens* in every life stage in each research location

**Table 2.** Important Value Index (IVI) of understory species in each location

| Species | Family | Kalikuning | Kaligendol | Balerante |
|---|---|---|---|---|
| *Ageratina adenophora* (Spreng.) R.M.King & H.Rob. | Asteraceae | | 2.95 | |
| *Alternanthera brasiliana* (L.) Kuntze | Amaranthaceae | 6.02 | 2.95 | |
| *Asplenium cuneatum* Lam. | Polypodiaceae | 1.64 | | |
| *Athyrium dilatatum* (Blume) Milde | Athyriaceae | | 3.20 | 19.26 |
| *Athyrium macrocarpum* (Blume) Bedd. | Athyriaceae | 5.68 | | 5.63 |
| *Borreria alata* (Aubl.) DC. | Rubiaceae | 9.05 | | |
| *Borreria repens* DC. | Rubiaceae | 10.49 | | |
| *Centella asiatica* (L.) Urb. | Apiaceae | 5.68 | | |
| *Cyperus compressus* L. | Cyperaceae | 23.39 | | |
| *Cyperus cyperoides* (L.) Kuntze | Cyperaceae | | 3.45 | 22.92 |
| *Cyperus haspan* L. | Cyperaceae | 2.74 | | |
| *Cyperus kyllinga* Endl. | Cyperaceae | 6.95 | | |
| *Cyperus pulcherrimus* Willd. ex Kunth | Cyperaceae | 24.35 | | 2.88 |
| *Digitaria fuscescens* (J.Presl) Henrard | Poaceae | | 4.19 | 5.41 |
| *Echinochloa crus-galli* (L.) P.Beauv. | Poaceae | | 5.43 | |
| *Eleocharis acutangula* (Roxb.) Schult. | Cyperaceae | | 3.94 | |
| *Elephantopus scaber* L. | Asteraceae | 13.77 | 3.94 | 14.57 |
| *Eleutheranthera ruderalis* (Sw.) Sch.Bip. | Asteraceae | | 3.94 | |
| *Eupatorium odoratum* L. | Asteraceae | | 3.20 | 3.68 |
| *Eupatorium riparium* Sch.Bip. ex Schnittsp. | Asteraceae | 2.06 | 5.90 | |
| *Galinsoga parviflora* Cav. | Asteraceae | | 20.44 | 12.11 |
| *Hymenachne acutigluma* (Steud.) Gilliland | Paniceae | | | 8.36 |
| *Imperata cylindrica* (L.) Raeusch. | Poaceae | | **65.95** | 23.06 |
| *Lindernia procumbens* (Krock.) Borbás | Scrophulariaceae | | 6.40 | |
| *Oxalis barrelieri* L. | Oxalidaceae | | 3.20 | |
| *Oxalis corniculata* L. | Oxalidaceae | 6.19 | | |
| *Panicum maximum* Nees | Poaceae | **51.23** | | **82.12** |
| *Paspalum distichum* L. | Poaceae | 1.89 | | |
| *Paspalum longifolium* Roxb. | Poaceae | | 14.81 | |
| *Pityrogramma tartarea* (Cav.) Maxon | Pteridaceae | | 6.40 | |
| *Polygala paniculata* L. | Polygalaceae | | 5.90 | |
| *Scirpus mucronatus* Host | Cyperaceae | 28.87 | 30.88 | |
| *Vernonia cinerea* (L.) Less. | Asteraceae | | 2.95 | |

Note: The bold value indicates the highest importance value index of species in each location

Cyperaceae and Asteraceae, both of which covered 21.21% of all species observed, were predominantly discovered in all locations, followed by Poaceae, which comprised 18.18% of all species explored. Athyriaceae, Rubiaceae, and Oxalidaceae each comprised 6.06% of all species identified (Table 2). The least prevalent families were Amaranthaceae, Polypodiaceae, Apiaceae, Paniaceae, Schropulariaceae, Pteridaceae, and Polygalaceae, each of which comprised only 3.03 % of all species discovered. The highest IVI in Kalikuning and Balerante was *P. maximum*, each of which comprised 25.62% and 41.06% of total IVI, respectively (Table 2). Another Poaceae member, *I. cylindrica*, also comprised the highest IVI (32.98%) of all species discovered in Kaligendol. The *E. scaber* was considered the most prevalent species, which was evenly distributed in all locations, indicating its universal adaptability to different elevations (Nugroho et al. 2022).

Extreme conditions, particularly intense heat, that occurred in the aftermath of the eruption could be a limitation to plant growth. Consequently, there are only a number of plant species thriving in this condition. Adapted plants are called thermophytes, which can be classified as obligate thermophytes (adaptable to extreme geothermal conditions), facultative thermophytes (adaptable to both extreme geothermal and non-geothermal habitats), and mesophytes (both obligate and facultative thermophytes) (Semenkov et al. 2021). Each species has a distinctive adaptation to this condition, leading to limited plant diversity. Cyperaceae and Poaceae are more obligate rather than facultative thermophytes (Semenkov et al. 2021). Cyperaceae is one of the most resilient species that can adapt to harsh conditions such as drought and hot environments (Xu et al. 2020), including amphibious environments (Wei et al. 2022). Asteraceae and Rubiaceae are classified as facultative thermophytes, contrasting to Polypodiaceae and Apiaceae, which are classified as mesophytes (Semenkov et al. 2021).

**Diversity and similarity level of understory species**

The highest heterogeneity and evenness were recorded in Kalikuning compared to other locations. It was associated with a higher abundance of understory species observed in Kalikuning. However, the richness of Kaligendol was almost 50% higher than that of other locations (Figure 4) due to the higher number of species observed in this location. Balerante showed a lower value for almost all indices except for evenness, which was higher than Kaligendol. It was attributed to the species abundance in Balerante which was most likely similar among species compared to other locations.

**Table 3.** Photosynthetic pathway of understory species in all locations

| Species | Family | Photosynthetic pathway | References |
|---|---|---|---|
| *Ageratina adenophora* | Asteraceae | C3 | Jiang et al. (2022) |
| *Alternanthera brasiliana* | Amaranthaceae | C3-C4 intermediate | Sage et al. (2007) |
| *Asplenium cuneatum* | Polypodiaceae | CAM | Ainuddin and Najwa (2009) |
| *Athyrium dilatatum* | Athyriaceae | C4 | Cavaco et al. (1998) |
| *Athyrium macrocarpum* | Athyriaceae | Unidentified | - |
| *Borreria alata* | Rubiaceae | C3 | Widaryanto (2017); Dilipkumar et al. (2020) |
| *Borreria repens* | Rubiaceae | C3 | Widaryanto (2017) |
| *Centella asiatica* | Apiaceae | Unidentified | - |
| *Cyperus compressus* | Cyperaceae | C4 | Liu and Wang (2006) |
| *Cyperus cyperoides* | Cyperaceae | C4 | Jung et al. (2016) |
| *Cyperus haspan* | Cyperaceae | C3 | Jung et al. (2016) |
| *Cyperus kyllinga* | Cyperaceae | C4 | Jung et al. (2016) |
| *Cyperus pulcherrimus* | Cyperaceae | C3 | Rudov et al. (2020) |
| *Digitaria fuscescens* | Poaceae | C4 | Crush and Rowarth (2007) |
| *Echinochloa crus-galli* | Poaceae | C4 | Korres et al. (2016) |
| *Eleocharis acutangula* | Cyperaceae | C3 | Nair and Viji (2023) |
| *Elephantopus scaber* | Asteraceae | C3 | Nguyen et al. (2023) |
| *Eleutheranthera ruderalis* | Asteraceae | Unidentified | - |
| *Eupatorium odoratum* | Asteraceae | C3 | CABI (2022a) |
| *Eupatorium riparium* | Asteraceae | Unidentified | - |
| *Galinsoga parviflora* | Asteraceae | C3 | Ripanda et al. (2023) |
| *Hymenachne acutigluma* | Paniceae | C3 | Klink and Joly (1989) |
| *Imperata cylindrica* | Poaceae | C4 | Liu and Wang (2006) |
| *Lindernia procumbens* | Scrophulariaceae | C3 | CABI (2022b) |
| *Oxalis barrelieri* | Oxalidaceae | C3 | Liu and Wang (2006) |
| *Oxalis corniculata* | Oxalidaceae | C3 | Liu and Wang (2006) |
| *Panicum maximum* | Poaceae | C4 | Crush and Rowarth (2007) |
| *Paspalum distichum* | Poaceae | C4 | Klink and Joly (1989) |
| *Paspalum longifolium* | Poaceae | C4 | Klink and Joly (1989) |
| *Pityrogramma tartarea* | Pteridaceae | Unidentified | - |
| *Polygala paniculata* | Polygalaceae | C3 | Wang (2005) |
| *Scirpus mucronatus* | Cyperaceae | C3 | Wang (2005) |
| *Vernonia cinerea* | Asteraceae | C3 | Hnatiuk (1980) |

Species discovered in Kaligendol depicted a higher resemblance to those of Kalikuning, by 20.5%, than that of Balerante (Figure 5). There were 4 species discovered in both Kaligendol and Kalikuning *viz*. *A. brasiliana*, *E. scaber*, *E. riparium* and *S. mucronatus*. Several species, for instance, *A. macrocarpum, C. cyperoides*, and *E. odoratum*, discovered in both locations, were also encountered in Balerante. The *H. acutigluma* was only discovered in Balerante. This species occurs in a wide range of elevations, from 500-3,000 masl (del Conosur 2014).

The different abundance and diversity of understory species in Balerante might be attributed to the distribution of *A. decurrens* and soil characteristics in this location. Total individuals of *A. decurrens* recorded in Balerante at each growth stage was higher compared to that of other locations, which in turn most likely promoted greater competition for light availability between *A. decurrens* and understory species. Approximately 48,48% and 30.30% of understory species observed in this study were classified as C3 and C4, respectively (Table 3). Most understory species classified as C4 plants in this study were from Cyperaceae and Poaceae families, indicating that higher light intensity is required to promote optimal growth (Romanowska and Wasilewska-Dębowska 2022). In the mountainous area, the number of C3 species was predominantly observed in higher altitudes (>2200 masl), as opposed to C4 species, which were mostly discovered in lower altitudes (830-2,000 masl) (Pizarro et al. 2020). Understory species classified as C3 are mostly broad-leaf species, such as *B. alata, H. acutigluma, O. barrelieri, O. corniculata, P. paniculata,* and *S. mucronatus* observed in this study (Wang 2005; Liu and Wang 2006; Crush and Rowarth 2007; Sage et al. 2007). The *A. brasiliana* was the only C3-C4 intermediate species observed in this study. The distinctive trait of this photosynthetic pathway is determined by its $CO_2$ compensation point, which ensues between C3 and C4; however, C3-C4 intermediate plants are closely related to their C4 siblings as it is considered as the evolutionary transition from C3 to C4 (Schlüter et al. 2017). The *A. cuneatum* was the only CAM species observed in this study. Most epiphytes, including fern species, are classified as CAM because of their adaptability to stress-prone conditions, particularly water stress (Krieg and Chambers 2022). On the contrary, 5 species were unidentified due to the lack of relevant studies conducted to observe their photosynthetic pathways. Identification of the photosynthetic pathways of understory species in a silvopastoral system is essential to determining adaptable species under shading in order to design the most appropriate stand management in the long term.

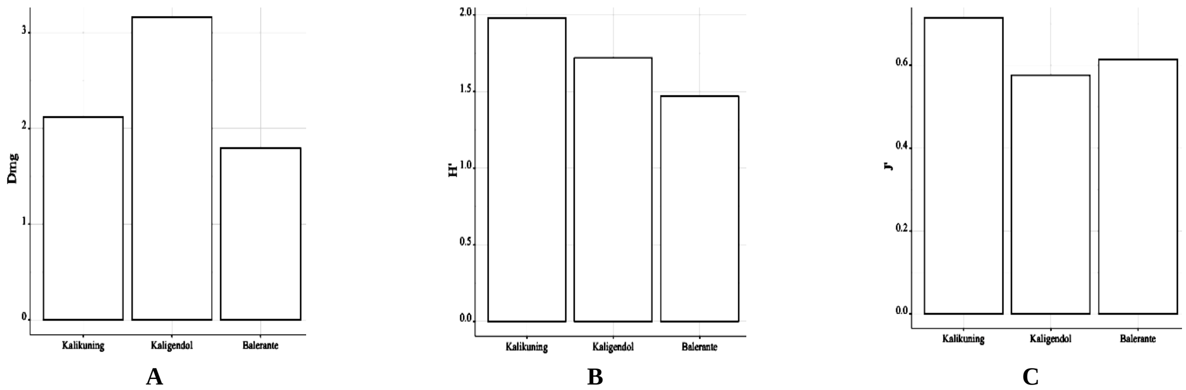


**Figure 4.** Biodiversity indices in terms of: A. Richness; B. Heterogeneity; and C. Evenness in three study site

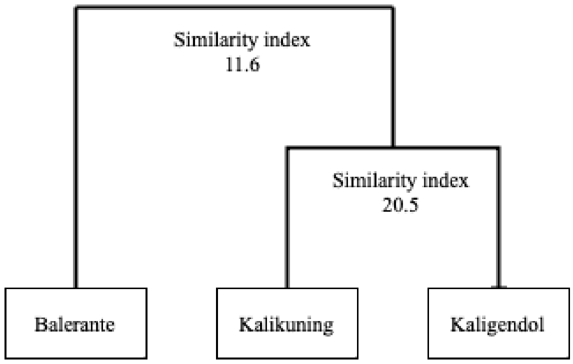


**Figure 5.** Similarity index of vegetation communities in three study sites

Soil chemical characteristics of Balerante were overall lower than other locations despite being ranked at the same level. It might contribute to lower diversity and abundance of understory species in Balerante. Lower diversity of understory species might be contrasting to the high abundance of *A. decurrens* in this location. The *A. decurrens* has high adaptability to poor soil quality, especially in degraded forestlands or marginal land, contributing to its high density. The aftermath of an eruption often results in the accumulation of volcanic ash, which can become compacted soon after interacting with rainwater, promoting the disconnection of underlying soil to the atmosphere and further depleting its nutrients and organic matter (Saputra et al. 2022). The similarity of plant composition depends on the species' tolerance to site conditions (Nugroho et al. 2022).

**Potential forage for livestock**

Identification of potential forage species in this study was based on its palatability which had been studied in the previous publications. Approximately 61% of species in all locations were palatable for livestock, 9% were toxic or unsafe, and the remaining 30% had no information on their status (Table 4). Species classified as palatable were commonly fed to livestock due to their high nutritional value and medicinal properties, for instance, *V. cinerea* and *G. parviflora*. Unpalatable species are those poisonous species that can produce toxic compounds within their metabolism either throughout their life or at certain age levels, such as *A. adenophora* and *C. compressus*. These species can potentially have toxic properties when consumed in large enough doses, especially in the roots (Soren et al. 2020). Species included in the unidentified classification are species for which no clear reference is found, including species of ferns that can generally be consumed by livestock. However, no clear reference is found.

Approximately 62.5%, 60%, and 73% of species encountered were classified as palatable in Kalikuning, Kaligendol, and Balerante, respectively, based on the number of species observed in each location. The top three species whose IVI values were the highest in each research location were identified as palatable species, *viz. P. maximum*, *I. cylindrica,* and *C. cyperoides*. On the contrary, unpalatable species had quite low IVI values, except for *C. compressus* species, whose IVI value was included in the three highest values in Kalikuning (23.39). Unpalatable species, for instance, *Phlomis cancellata* Bunge, was recorded to induce associational defense, resulting in lower biodiversity of neighboring communities compared to communities without it, especially in grazing conditions (Erfanian et al. 2021). This type of associational effect was indicated by a higher abundance of focal species near the less preferred species (unpalatable species) as a defense behavior against herbivores (Huang et al. 2018). Vegetation diversity in silvopastoral system has been regarded as one of the significant contributing factors to livestock growth and productivity. Integrating leguminous trees in the silvopastoral system is proven to increase weight gain and milk production in the cut-and-carry system. Besides, diversified fodder sources in silvopastoral systems can be a preventive measure to protect livestock against parasites or diseases due to their antiparasitic properties (Villalba et al. 2014). Fodder species selection in silvopasture is pivotal to providing a nutritious diet for livestock (Cuchillo-Hilario et al. 2018).

**Table 4.** Palatability identification of forage species in all locations

| Species | Family | Palatability | Reference |
|---|---|---|---|
| *Ageratina adenophora* | Asteraceae | Unpalatable | Ren et al. (2021) |
| *Alternanthera brasiliana* | Amaranthaceae | Palatable | Adejoke et al. (2018) |
| *Asplenium cuneatum* | Polypodiaceae | Unidentified | - |
| *Athyrium dilatatum* | Athyriaceae | Unidentified | - |
| *Athyrium macrocarpum* | Athyriaceae | Unidentified | - |
| *Borreria alata* | Rubiaceae | Palatable | Abbood et al. (2017) |
| *Borreria repens* | Rubiaceae | Palatable | Lobo et al. (2024) |
| *Centella asiatica* | Apiaceae | Palatable | Boonyarattanasoonthorn et al. (2022) |
| *Cyperus compressus* | Cyperaceae | Unpalatable | Soren et al. (2020) |
| *Cyperus cyperoides* | Cyperaceae | Palatable | CABI (2021a) |
| *Cyperus haspan* | Cyperaceae | Palatable | CABI (2021b) |
| *Cyperus kyllinga* | Cyperaceae | Unidentified | - |
| *Cyperus pulcherrimus* | Cyperaceae | Unidentified | - |
| *Digitaria fuscescens* | Poaceae | Palatable | Muhakka et al. (2020) |
| *Echinochloa crus-galli* | Poaceae | Unpalatable | Wu et al. (2023) |
| *Eleocharis acutangula* | Cyperaceae | Palatable | Muhakka et al. (2020) |
| *Elephantopus scaber* | Asteraceae | Palatable | Hiradeve and Rangari (2014) |
| *Eleutheranthera ruderalis* | Asteraceae | Palatable | Rusdi et al. (2016) |
| *Eupatorium odoratum* | Asteraceae | Palatable | Aro et al. (2009) |
| *Eupatorium riparium* | Asteraceae | Palatable | Ngawit and Farida (2022) |
| *Galinsoga parviflora* | Asteraceae | Palatable | Ripanda et al. (2023) |
| *Hymenachne acutigluma* | Paniceae | Palatable | Riswandi (2014) |
| *Imperata cylindrica* | Poaceae | Palatable | Rusdy (2020) |
| *Lindernia procumbens* | Scrophulariaceae | Unidentified | - |
| *Oxalis barrelieri* | Oxalidaceae | Palatable | Jain et al. (2010) |
| *Oxalis corniculata* | Oxalidaceae | Palatable | Sarkar et al. (2020) |
| *Panicum maximum* | Poaceae | Palatable | Sokupa et al. (2023) |
| *Paspalum distichum* | Poaceae | Palatable | Parker (2009) |
| *Paspalum longifolium* | Poaceae | Unidentified | - |
| *Pityrogramma tartarea* | Pteridaceae | Unidentified | - |
| *Polygala paniculata* | Polygalaceae | Unidentified | - |
| *Scirpus mucronatus* | Cyperaceae | Unidentified | - |
| *Vernonia cinerea* | Asteraceae | Palatable | Ediriweera et al. (2020) |

The detrimental effect of the Mount Merapi eruption transformed the vegetation structure, composition, and diversity through primary succession. Furthermore, it resulted in adverse effects on soil characteristics due to the accumulation of volcanic materials, which subsequently promoted different soil quality alterations depending on the severity of exposure. The *A. decurrens* invading the exposed area after the eruption has created a suitable agroecosystem for understory species, which were mostly harvested as fodder. High diversity of vegetation components in silvopastoral systems, either tree or understory species, is deemed essential to maintain the sustainability and productivity of the system. However, shade trees and forage species selection are also important to prevent growth inhibition either by resource competition between components or allelopathy. Enrichment planting in the post-eruption area is urged to improve both diversity and soil quality without neglecting periodic stand management, such as pruning, especially in the most foraged area.

## ACKNOWLEDGEMENTS

The authors would like to express their gratitude and appreciation to the *Lembaga Pengelola Dana Pendidikan* (The Indonesia Endowment Fund for Education) under the Ministry of Finance, *Beasiswa Pendidikan Indonesia* (Indonesian Education Scholarship Program) provided by Ministry of Education, Culture, Research, and Technology Republic of Indonesia, and *Rekognisi Tugas Akhir 2019* (Thesis Recognition Program 2019) provided by Universitas Gadjah Mada, Yogyakarta, Indonesia for facilitating this research through the fund incentive for international journal as one of items listed in scholarship's letter of guarantee. We wish to thank Universitas Gadjah Mada students who participated as surveyors in this research.

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