Vol. 14(1): 193-210, January 2026 DOI: https://doi.org/10.23960/jsl.v14i1.1343

Jurnal Sylva Lestari

P-ISSN: 2339-0913
E-ISSN: 2549-5747

Journal homepage: https://sylvalestari.fp.unila.ac.id

Full Length Research Article

Early Ecological Responses to Vegetation Enrichment for Pollinator Habitat Recovery using *Tetragonula biroi* in Community Agroforestry Systems

Andi Masniawati[1], Andi Gita Maulidyah Indraswari Suhri[1,*], Yusran[2], Andi Hasdiansyah[3]
Fitha Febrilia Ruli[1], Septiantina Dyah Riendriasari[4], Magdalena Litaay[1]

[1] Department of Biology, Faculty of Mathematics and Natural Sciences, Hasanuddin University, South Sulawesi, Indonesia
[2] Study Program of Forest Management, Faculty of Forestry, Hasanuddin University, Makassar, Indonesia
[3] Master's Program of Pedagogy, Universitas Muhammadiyah Parepare, South Sulawesi, Indonesia
[4] Research Centre for Applied Zoology, National Research and Innovation Agency, Bogor, West Java, Indonesia
[*] Corresponding Author. E-mail address: gitamaulidyah@unhas.ac.id

ARTICLE HISTORY:
Received: 8 November 2025
Peer review completed: 7 January 2026
Received in revised form: 24 January 2026
Accepted: 30 January 2026

KEYWORDS:
Agroforestry
Meliponiculture
Pollination
Tetragonula biroi
Tropical restoration
Vegetation enrichment

ABSTRACT

Pollination decline has become a major ecological concern in tropical agroforestry systems, where habitat simplification reduces floral diversity and threatens pollinator stability. This study aimed to evaluate early ecological responses to vegetation enrichment designed to restore pollination function in a community-managed agroforestry landscape in South Sulawesi, Indonesia. A paired-plot experiment was established to compare two adjacent plots (each 0.25 ha), an enriched plot and a control plot, in which floral diversity, foraging activity, colony productivity, and microclimatic parameters were monitored from September to November 2025. Indices of diversity and comparative statistical tests were used to analyse ecological variables and assess treatment effects. Shannon-Wiener floral diversity indices (H') increased from 1.45 to 1.66 after vegetation enrichment, resulting in greater phenological overlap in relation to the control plots as well. These changes correspond to a substantially increased rate of stingless bee (*Tetragonula biroi*) visits and a higher return frequency in enriched plots ($p < 0.05$). An increase in foraging activity was observed, with a significantly greater extension of the brood area and a rise in honey production, reflecting improved colony performance. Also, microclimatic measurements indicated lower temporal variance in ambient temperature and light intensity under enriched vegetation, suggesting a dampening effect on more stable foraging conditions. In general, these results imply that small-scale vegetation can induce an early return to functioning through a trade-off effect on resource diversity, colony strength, and environmental stability in the context of community agroforestry systems and do not contradict community-based landscape management.

1. Introduction

Pollination is a crucial ecological process that supports the reproductive success of flowering plants and the productivity of land-based ecosystems. Worldwide, more than 75% of key food crops and over 85% of trees in tropical forests rely, at least in part, on animal-pollinated pollination (Catarino et al. 2019; Nicholson and Egan 2019). The ongoing decline in pollinator populations represents not only a biodiversity crisis but also poses a significant threat to ecosystem stability and food security (Diyaolu and Folarin 2024; IPBES 2022; Liang et al. 2023). The degradation of habitats, the intensification of land use, and contamination from pesticides have resulted in substantial reductions in nesting and floral resources, particularly in tropical regions where small-scale farmers manage extensive areas of the landscape. These effects are especially pronounced in Southeast Asia, where deforestation and the expansion of monocultures have simplified habitats and disrupted the year-round availability of floral resources necessary to sustain pollinator communities (De Moraes et al. 2020; Velastegui-Montoya et al. 2022).

Stingless bees (tribe Meliponini) hold significant ecological and socio-economic value among tropical pollinators. They serve as essential pollinators for native forests, fruit trees, and various cash crops in Southeast Asia (Roubik 2022; Quezada-Euán et al. 2018). Their foraging activities significantly enhance plant reproductive success and forest regeneration, while also supporting the livelihoods of rural communities through the production of honey, propolis, and wax (Valido et al. 2019). Nevertheless, their populations are experiencing a significant decline due to the combined impacts of habitat fragmentation, agricultural intensification, and the loss of nesting sites (Gebremariam 2024; Nath et al. 2022). In Indonesia, although Social Forestry programs extensively cover community-managed forests, many agroforestry landscapes remain dominated by economically motivated vegetation with limited floral diversity. This situation constrains the stability of pollinator foraging and the overall functioning of ecosystems.

Vegetation enrichment, defined as the strategic reintroduction of native or nectariferous species into simplified landscapes, has emerged as a promising and cost-effective intervention for restoring ecosystem functionality (Brooker et al. 2021; Hartoyo et al. 2025; Omer et al. 2024). Enrichment planting can stabilize pollinator visitation patterns by enhancing floral resource diversity and temporal continuity. However, empirical evidence directly linking such interventions to functional outcomes, including pollinator activity, colony productivity, or ecosystem recovery, remains limited (Venjakob et al. 2016). In Southeast Asian agroforestry systems, enrichment planting has been associated with increased pollinator visitation and improved floral resource availability, particularly for stingless bees in cacao- and fruit-based agroforests. Studies from Indonesia and neighboring regions suggest that increasing plant species heterogeneity can extend flowering periods and support more consistent pollinator foraging activity. Nonetheless, these responses are often inferred rather than directly quantified. Most studies on tropical systems have emphasized vegetation structure, biomass accumulation, or the social adoption of meliponiculture, with little attention to the mechanistic pathways through which enrichment supports pollination function (Bergamo et al. 2021).

The identified research gap holds significant implications for community-based forestry initiatives. In Indonesia, social forestry endeavors to harmonize biodiversity conservation, livelihood enhancement, and local stewardship. Nevertheless, the assessment of restoration success frequently emphasizes vegetation growth rather than ecosystem processes (Suhri 2025). Pollination, as a dynamic ecological function, serves as a more sensitive indicator of restoration progress, as it signifies the re-establishment of mutualistic interactions between plants and insects (Lau et al. 2023). Consequently, quantifying pollinators' early responses to enrichment interventions is crucial for determining whether community agroforestry landscapes are progressing towards functional recovery.

Despite the growing interest in stingless bee cultivation (meliponiculture) as a means of community empowerment, there remains a paucity of scientific evidence regarding its ecological efficacy. Previous research has indicated that *T. biroi*, a prevalent stingless bee species in Sulawesi, exhibits a strong response to local floral availability and microclimatic conditions (Agussalim et al. 2021). However, there is a dearth of experimental studies examining the impact of vegetation enrichment on foraging stability, brood development, and honey productivity within actual community management frameworks. Furthermore, the temporal aspect of these responses has been largely overlooked, particularly during the initial months following habitat enrichment, when plant establishment and resource heterogeneity begin to emerge. Addressing this gap necessitates a functional ecological perspective that extends beyond merely documenting species presence to assessing how enrichment influences ecosystem processes. The early response phase, typically within the first four months post-enrichment, offers critical insights into whether restored habitats begin to support pollinator activity and whether these effects are discernible before full canopy closure or flowering equilibrium (León-Canul et al. 2023). Observations during this phase can illuminate the onset of ecological feedback, such as increased foraging rates or brood development, which may indicate the potential trajectory of long-term restoration outcomes.

Consequently, this research sought to assess the initial ecological responses to vegetation enrichment within a community-based agroforestry system in South Sulawesi, Indonesia. Specifically, it examines (1) short-term variations in floral diversity and phenological overlap, (2) the foraging behavior and colony performance of *T. biroi*, and (3) the interconnections between floral heterogeneity, microclimatic stability, and pollinator productivity. The study was conducted in Pucak Village, Maros Regency, a representative agroforestry site where local farmer groups manage both agricultural and conservation plots.

In contrast to previous meliponiculture studies that focus on technical training or community outcomes, this study employs an experimental functional-ecology framework, considering stingless bee colonies as bioindicators of habitat recovery rather than production units. The short-term focus constitutes the initial phase of a longitudinal program aimed at monitoring the restoration of pollination function across multiple flowering seasons. By correlating ecological data with habitat interventions, this research provides empirical evidence of the initial functional trajectory of enriched agroforestry systems. Ultimately, the findings are anticipated to enhance understanding of how vegetation enrichment influences pollinator–plant interactions in tropical landscapes and how such interventions can be implemented in community forestry programs. This approach is consistent with the Post-2020 Global Biodiversity Framework and Indonesia's National Strategy for Pollinator Conservation, both of which prioritize the restoration of ecosystem functions over mere structural reforestation. The results offer both theoretical and practical insights into how community-based restoration can simultaneously enhance biodiversity, ecological resilience, and livelihood security in tropical agroforestry landscapes.

2. Materials and Methods

The study was conducted from September to November 2025 in Pucak Village, Maros Regency, South Sulawesi, Indonesia (5°00′–5°05′ S; 119°47′–119°52′ E). The research location is situated within the Maros–Pangkep karst uplands, at an elevation ranging from 280 to 320 meters above sea level. The area has a humid tropical climate, with an average annual precipitation of approximately 3,000 mm, a mean temperature of 27 ± 2 °C, and a relative humidity of around 78%. The local landscape comprises mixed agroforestry mosaics predominantly featuring *Theobroma cacao*, *Cocos nucifera*, *Musa paradisiaca*, *Carica papaya*, and other fruit trees, interspersed with patches of secondary forest.

2.1. Experimental Design

An experimental design utilizing paired plots was employed to assess initial ecological responses to vegetation enrichment. This design was executed at a singular agroforestry site as a within-site paired comparison, comprising one enriched plot and one adjacent control plot, to evaluate early ecological responses under consistent environmental conditions. The study was not structured as a replicated block experiment across multiple sites, thus limiting inferences to short-term, within-site contrasts. Two adjacent plots, each measuring 0.25 hectares, were established: one enriched plot, incorporating selected flowering and horticultural species, and one control plot representing the existing community agroforestry without enrichment (**Fig. 1**). The enrichment treatment was initiated in early September 2025, concentrating on plants that offer high floral-reward potential (nectar and pollen) and possess short vegetative cycles suitable for the tropical lowland environment. The species assemblage included chili pepper (*Capsicum frutescens* L.), Duchesne (pumpkin) (*Cucurbita moschata*), commonly known as chain-of-love (*Antigonon leptopus*, yellow trumpet vine (*Allamanda cathartica* L.), cucumber (*Cucumis sativus* L.), tomato (*Solanum lycopersicum* L.), and African marigold (*Tagetes erecta* L.).

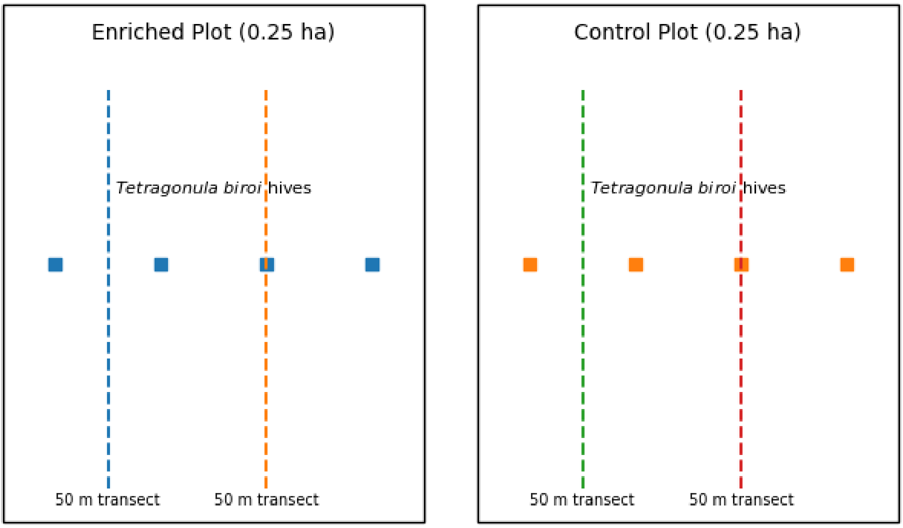

Fig. 1. Schematic layout of the paired-plot experimental design. The schematic layout is provided to clarify the spatial arrangement of plots, transects, vegetation enrichment, and hive placement.

The selected species were chosen due to their complementary flowering phenology, diverse floral morphology, and significant attractiveness to generalist pollinators, particularly *T. biroi*. The plants were systematically arranged in alternating rows, incorporating vine, shrub, and herbaceous forms, to ensure continuous blooming throughout the observation period. Spacing followed practical agroforestry guidelines: 1.5–2 m for herbaceous and shrub species (*Capsicum*, *Tagetes*, *Solanum*) and 3–4 m for trailing or climbing vines (*Antigonon*, *Allamanda*, *Cucurbita*, *Cucumis*). Thirty colonies of *T. biroi* were established in standardized wooden hives measuring 20 cm × 12 cm × 15 cm for each treatment. These colonies were sourced from local meliponiculture units in Maros to ensure compatibility with the regional flora. The hives were systematically distributed across the plots, with approximately one hive per 80 m^2, and oriented southward to standardize sun exposure. All colonies underwent a two-week acclimatization period before the commencement of observations.

The agroforestry system comprised a diverse array of tree, shrub, and herbaceous plant species, typically managed by local farmers. The tree and shrub components were predominantly composed of perennial species cultivated for fruit production, shade, and household use, including coconut (*Cocos nucifera*), banana (*Musa* spp.), cacao (*Theobroma cacao*), and various locally grown timber and multipurpose tree species. The herbaceous and understory vegetation included both spontaneous weeds and cultivated annual crops, which collectively enhanced floral resource availability for pollinators. Vegetation data were collected using a systematic plot-based methodology. Within each plot, plant species composition was documented along established transects, with nested subplots positioned at regular intervals. All flowering plant species encountered within subplots were identified to the species or morphospecies level, and their abundance was recorded. These data were utilized to characterize plant species composition and floral resource availability within the agroforestry system during the observation period.

2.2. Floral Resource and Phenology Monitoring

Floral resource dynamics were systematically monitored monthly from September to November 2025 through subplot sampling. Data on vegetation and floral resources were collected using line transects. Along each 50 m transect, nested subplots measuring 2 m × 2 m were systematically positioned at 10 m intervals to record plant species composition and flowering abundance. This methodology resulted in five subplots per transect and a total of ten subplots per plot for each sampling period. All flowering individuals within each subplot were identified and counted, including herbaceous plants, shrubs, climbers, and tree species, provided that flowering structures were present within the vertical and horizontal boundaries of the sampling unit. Large trees were included in the diversity and evenness calculations only when their flowers were present within the observable strata relevant to pollinator foraging. Floral diversity was quantified using the Shannon–Wiener diversity index (H'), calculated with the natural logarithm (ln), along with the corresponding evenness index (E). To assess the temporal overlap in blooming among species, a phenological overlap index was calculated (Yarnell et al. 2013). The same trained observer conducted all floral counts and phenological scoring throughout the study period to minimize observer bias. This index provides a measure of resource continuity across the sampling period, reflecting the potential stability of pollinator foraging resources within the enriched plots.

2.3. Pollinator Activity and Foraging Observations

Pollinator activity was assessed through fixed-point visual observation conducted exclusively under comparable favorable weather conditions, characterized by clear to partly cloudy skies, no rainfall, and low wind intensity. These observations were conducted between 08:00 and 11:00 a.m., which aligns with the daily foraging peak of stingless bees. Observation quadrats (1 m^2) were established every 10 m along each transect. Each quadrat was observed for 10 min, and all flower-visiting insects were recorded, with specific attention to *T. biroi*. The number of visits per species and per unit time was expressed as the visitation frequency (visits 10 min^{-1} m^{-2}). At the colony level, the returning-forager rate (individuals min^{-1}) was quantified by counting incoming bees at hive entrances for three consecutive minutes per colony, repeated three times monthly to derive the mean activity. Identification of bee visitors was conducted using a handheld magnifier (10×) and reference to A Key to the Genera and Subgenera of Stingless Bees in Indonesia (Engel et al. 2018). This integration of field- and colony-level metrics facilitated the evaluation of both pollinator responses to resource enrichment and the stability of hive foraging, which serve as two complementary indicators of initial ecological function.

2.4.Colony Strength and Productivity

Monthly evaluations of colony conditions encompassed brood-cell count, the number of pollen pots, and the volume of honey pots, adhering to non-destructive inspection protocols (Roubik 2023). Honey production per cycle was quantified volumetrically using 20 ml sterile syringes and reported as mL per colony per month (ml/colony/month). To minimize disturbance, no more than 20% of the total honey volume was extracted during any single sampling event. Measurements were standardized to facilitate cross-plot comparisons of productivity and colony vigor (CV).

2.5. Microclimatic Measurements

Throughout the study period, environmental covariates were continuously recorded. A HOBO MX2301 data logger (Onset Computer Corporation, USA) was installed at the canopy height in each plot, with one logger per plot, to measure temperature (°C), relative humidity (%), and solar radiation intensity (lux) at 30-minute intervals. The data were averaged daily to generate microclimatic profiles representative of each plot. While a single logger per plot may not capture micro-scale variation, it offers a consistent representation of plot-level microclimatic conditions pertinent to foraging activity. These environmental data were employed as covariates in subsequent analyses to differentiate between biotic responses to enrichment and those attributable to abiotic variability.

2.6. Data Analysis

All data analyses were conducted utilizing R (version 4.3.3). Floral diversity indices, specifically H' and E, were computed for each plot and month. Differences in treatment between enriched and control plots for floral density, visitation frequency, and honey yield were assessed using independent-samples t-tests, contingent on normality assumptions verified by the Shapiro–Wilk test. For analyses where normality assumptions were not met, nonparametric Mann–Whitney U tests were employed. The associations between floral diversity (H') and pollinator visitation rate, as well as between visitation and honey yield, were examined using Pearson’s correlation coefficients, with a significance threshold set at 5% ($p < 0.05$). To assess the impact of floral diversity and microclimatic factors on foraging activity, a multiple linear regression model was applied, as represented by Equation 1:

$$F = \beta_0 + \beta_1 H' + \beta_2 T + \beta_3 RH + \varepsilon \quad (1)$$

where F represents the rate of foraging, H' denotes floral diversity, T signifies the average temperature, and RH indicates relative humidity. All visual depictions of temporal patterns, including floral density, visitation rate, and colony productivity, were generated using the ggplot2 package, which displayed the mean values with 95% confidence intervals. Due to the limited observation period, the analysis focused on initial directional responses, such as increases or stabilization in pollinator activity and floral diversity, rather than fully developed seasonal equilibria.

3. Results and Discussion

3.1. Floral Diversity and Phenological Overlap

In the enriched plots, the Shannon–Wiener diversity index (H') rose from 1.45 ± 0.07 in September to 1.66 ± 0.05 by November. Conversely, the control plots showed a smaller increase, moving from 1.38 ± 0.06 to 1.41 ± 0.08 during the same timeframe. Flower density, measured as open flowers per square meter, increased from 120 ± 15 to 190 ± 20 flowers/m^2 in the enriched plots, while in the control plots it increased from 110 ± 12 to 125 ± 18 flowers/m^2. The phenological overlap index, known as Pianka's index, reached 0.68 ± 0.03 in the enriched plots, compared to 0.52 ± 0.04 in the control plots (**Fig. 2**).

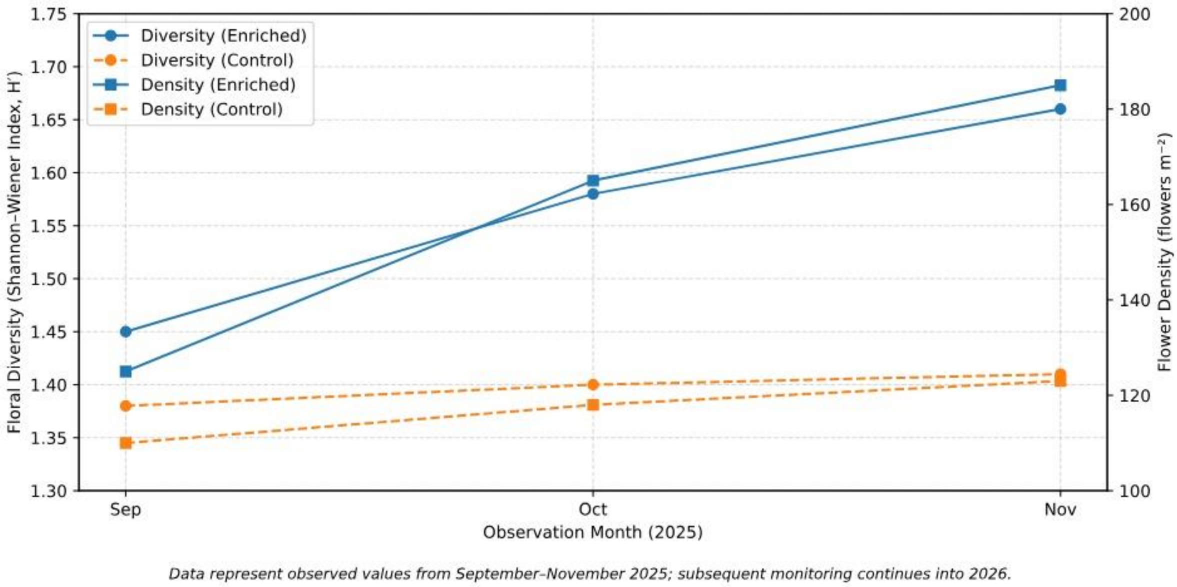

Fig. 2. Temporal trends in floral diversity and flower density between enriched and control plots in a community-managed agroforestry system.

The results provide compelling preliminary evidence that targeted vegetation enrichment within a community-managed agroforestry system can rapidly enhance floral resource heterogeneity and its temporal continuity. Notably, the magnitude of these increases corresponds with the observed rise in pollinator visitation and forager return rates discussed in the subsequent section, indicating that the detected changes are ecologically significant for pollination processes. The concurrent increase in both Shannon–Wiener diversity (H') and flower density aligns with restoration ecology expectations, suggesting that greater structural and compositional complexity supports more abundant and stable floral resource availability (Teuscher et al. 2016). The heightened phenological overlap observed in the enriched plots further demonstrates that the introduced assemblage of horticultural and ornamental species successfully extended the blooming window, a crucial factor for pollinator foraging stability (Bożek and Denisow 2023). From a functional restoration perspective, this trend is ecologically significant because improving floral continuity helps mitigate temporal resource gaps that typically limit pollinator activity in simplified agroecosystems (Kovács-Hostyánszki et al. 2017). However, these patterns should be viewed as early functional responses rather than full ecosystem recovery, given the short monitoring period and limited temporal scope of the current phase. Nonetheless, the positive trajectory establishes a credible foundation for linking habitat enhancement to pollinator-mediated ecosystem functions in subsequent analyses. In this context, the enrichment plots already exhibit the structural preconditions and early functional signals necessary for the recovery of pollination dynamics.

3.2 Foraging Activity of T. biroi

In the enriched plots, visitation frequency by bees increased from approximately 5.2 visits per 10 minutes per m^2 in September to 8.4 by the end of the observation period (November 2025). In control plots, the increase was modest, from approximately 4.9 to 5.6. Similarly, the forager return rate to hives in enriched plots increased from about 1.2 individuals/min to ~2.0, whereas control plots rose from ~1.1 to ~1.3 individuals/min. Statistical tests (independent-samples t-tests) confirmed significant differences between enriched and control plots by December ($p < 0.05$) (**Fig. 3**). Observed relationships between vegetation enrichment and foraging metrics were examined using monthly mean values pooled across the three-month observation period ($n = 3$ per treatment), rather than within-month regression analyses, consistent with the study's emphasis on early temporal responses.

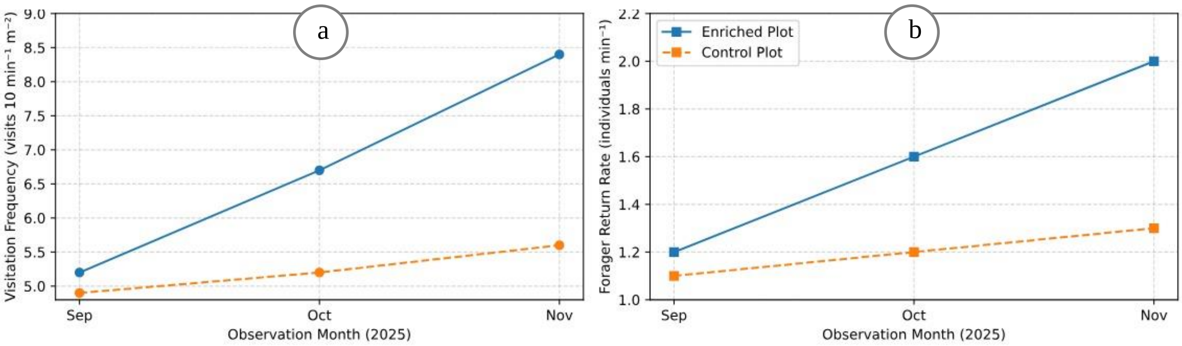

Fig. 3. Temporal variation in foraging activity of *T. biroi* between enriched and control plots in a community-managed agroforestry system: (a) Shows visitation frequency on flowering plants, (b) Presents hive forager return rates, both highlighting the consistent increase in the enriched plots.

Visitation frequency and hive-entrance forager return rates both increased consistently in the enriched plots over the three months, whereas the control plots showed only modest changes. Specifically, the mean visitation frequency on flowering plants rose from 5.2 to 8.4 visits 10 min^{-1} m^{-2} in enriched plots compared with 4.9 to 5.6 in controls. In enriched plots, the rate at which foragers returned increased from 1.2 to 2.0 individuals per minute, compared to 1.1 to 1.3 in control plots ($p < 0.05$). These paired behavioral metrics illustrate both resource utilization (floral visitation) and foraging effort at the colony level (return rate), indicating a consistent and early functional response to vegetation enrichment. From an ecological perspective, these findings align with the well-established sensitivity of stingless bees to local changes in resource availability and habitat structure. Traditional syntheses indicate that Meliponini exhibit generalized flower-visiting behavior at the colony level but demonstrate strong foraging optimization at the individual level, with recruitment and flight behavior influenced by reward distribution and microhabitat conditions

(Hrncir et al. 2016). Controlled studies on *T. biroi* have further shown that foraging intensity is influenced by the spatial arrangement of resources (distance and height relative to the hive), supporting the notion that enhanced nearby resource fields lead to rapid increases in activity (Ciar et al. 2013). In our research, the enrichment with a diverse array of horticultural and ornamental species—selected for their high floral reward potential, complementary flowering phenology, and compatibility with mixed agroforestry vegetation (as detailed in Section 2.2)—likely enhanced both the abundance of rewards and the detectability of foragers within the colonies' effective search area, mechanisms known to enhance visitation and return rates (Basari et al. 2018; Kaluza et al. 2016).

From a land-use perspective, the observed pattern aligns with broader evidence suggesting that diverse agroforestry systems generally enhance pollinator activity compared to simplified monocultures, as they provide more continuous and varied forage (Kovács-Hostyánszki et al. 2017). Enhancing vegetation does more than merely add flowers; it modifies the temporal and structural characteristics of resources available to foragers. The noted increase in phenological overlap indicates an extended "bloom window," which is crucial for stingless bees that forage daily and prefer consistent, short-range rewards (Heard 1999). The accompanying microclimatic moderation we observed likely reinforced this effect: reduced thermal and humidity fluctuations under enriched vegetation can decrease foraging costs and protect nectar from rapid drying or dilution, thereby enhancing net foraging returns (Bożek and Denisow 2023). However, a cautious interpretation is warranted. While increased visitation and return rates suggest functional improvement, they are not sufficient to demonstrate enhanced pollination service delivery to plants (fruit set and seed quality). Numerous studies have highlighted that pollination outcomes can be constrained by pollen availability, floral structure, or environmental stress, even with increased visits (Kovács-Hostyánszki et al. 2017).

Additionally, our activity metrics reflect early adjustments within a brief observation period; seasonal dynamics, colony demographics, and landscape-scale resource changes may amplify or diminish these responses over longer durations (Heard 1999). Therefore, although the current findings provide strong early-phase functional signals, they should be viewed as part of an ongoing trajectory rather than as evidence of complete ecosystem service recovery. Integrating these lines of evidence, the enriched plots present a credible mechanism linking habitat enhancement to pollinator behavior: improved floral diversity and continuity lead to higher foraging activity under more favorable microclimates. To explicitly quantify this connection, we analyzed the relationship between floral diversity (H') and foraging rate across treatments (**Fig. 4**).

A notable positive correlation was identified between floral diversity (H') and foraging rate across different treatments, with a significantly steeper gradient observed in enriched plots ($r = 0.93$, $p < 0.05$). This result supports the idea that enhancing vegetation improves the functional connection between habitat quality and pollinator activity. Essentially, *T. biroi* colonies in environments with greater floral diversity exhibited both increased foraging intensity and more consistent foraging traffic over time. Similar patterns between floral diversity and bee visitation have been observed in tropical agroforestry mosaics, where greater floral heterogeneity encourages resource complementarity and sustained energy flow within pollinator groups (Bonatti et al. 2024; Bożek and Denisow 2023; Buchori et al. 2022). Thus, the observed correlation signifies not just a behavioral change but an initial functional linkage between community-level vegetation restoration and the potential for pollinator ecosystem services. This linkage is crucial for the success of restoration efforts, as enhanced floral diversity improves foraging efficiency and colony nutrition, which, in turn, support brood development and long-term colony productivity (Lau et al. 2023; McIlwain et al. 2024). In line with this functional continuum, the following section examines whether the increased foraging rates observed here led to measurable changes in colony performance, specifically in brood expansion and honey yield, as comprehensive indicators of pollination recovery.

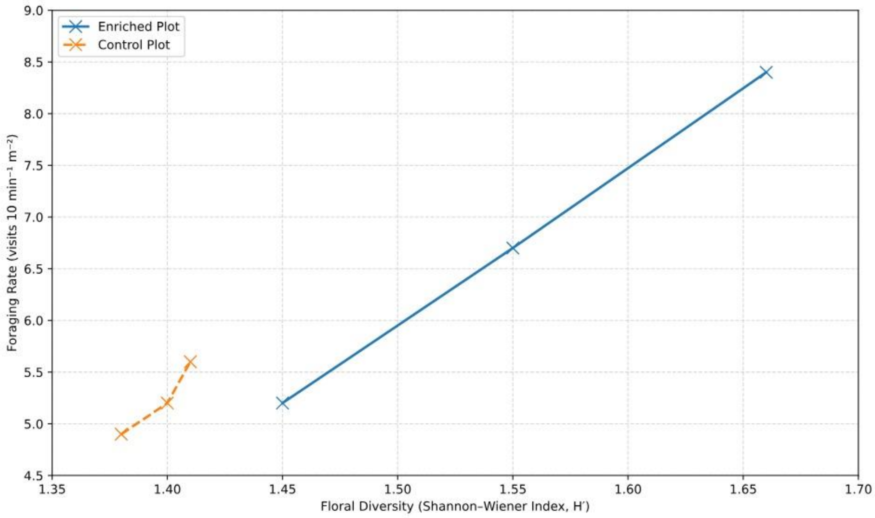

Fig. 4. Relationship between floral diversity and foraging rate in enriched and control plots within a community-managed agroforestry system.

3.3. Colony Productivity and Brood Indicators

Colony-level responses reflected the behavioral patterns observed in the field. The brood area in the enriched plots expanded significantly from 320 ± 25 cm^2 in September to 505 ± 30 cm^2 in November, whereas the control plots exhibited a more modest increase from 310 ± 22 cm^2 to 350 ± 28 cm^2 over the same period. Similarly, the mean honey pot volume increased by approximately 64% in enriched plots, rising from 180 ± 15 ml to 295 ± 20 ml per hive. In contrast, control plots showed a more modest increase of about 21% (from 170 ± 14 ml to 205 ± 18 ml) over the same period ($p < 0.05$) (**Fig. 5**). These trends suggest that vegetation enrichment not only enhances foraging activity but also improves the internal productivity of *T. biroi* colonies, likely through improved pollen and nectar intake that fuels brood rearing and energy storage. The strong correspondence between field-level floral availability and within-hive productivity supports the functional restoration hypothesis, which posits that an enhanced vegetation structure increases resource flow to pollinator colonies (Potts et al. 2016). Stingless bees rely on the continuous availability of nectar and pollen to maintain larval provisioning and wax production; even short interruptions can reduce brood survival or trigger colony absconding (Lima and Marchioro 2021; Main et al. 2019). In the present study, the enriched plots provided a more temporally stable bloom sequence, likely maintaining a consistent pollen inflow and permitting uninterrupted brood expansion. This mechanism resembles that described by Wongsa et al. (2023), who demonstrated that *Tetragonula* colonies in diversified agroforests showed higher brood cell turnover and greater honey yields than those in monoculture environments. The enhanced honey yield in the enriched plots also suggests a metabolic response at the colony level. Higher nectar inflow enables greater conversion to stored honey, which serves as both an energy buffer and protection against resource scarcity (Papa et al. 2022). From an ecological services perspective, this improvement signifies not only greater colony resilience but also an expanding pollination potential in local agroecosystems.

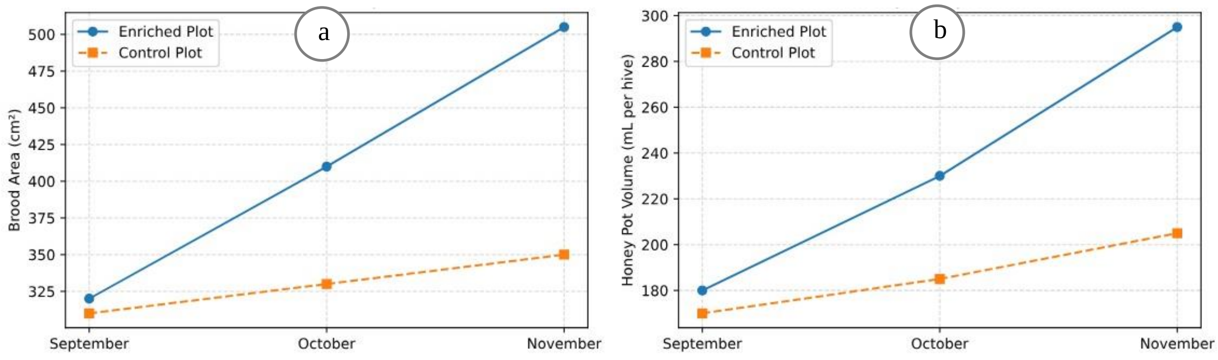

Fig. 5. Temporal changes in (a) brood development and (b) honey production for *T. biroi* colonies in enriched and control plots.

Nevertheless, these advancements should be regarded as preliminary functional responses rather than complete restoration outcomes. Given that these responses indicate early-stage conditions, it is expected that colony productivity will either stabilize or fluctuate as vegetation structure and the dynamics of floral resources continue to develop. Colony productivity encompasses both environmental and intrinsic factors, such as the queen's fertility, the age of the colony, and inter-colony variations, which can only be comprehensively understood through prolonged observation (Diyaolu 2024; Lima and Marchioro 2021). Alterations in floral composition due to seasonal changes or climatic stress may affect foraging efficiency and brood dynamics. Therefore, while the current data demonstrate clear short-term benefits of enhancing vegetation, they mark the beginning of a multi-year journey towards sustainable pollination. Enhancing vegetation rapidly translates into landscape-level improvements in floral diversity and foraging activity, resulting in tangible increases in colony brood and honey production. These findings underscore the critical role of improving habitat quality as a fundamental driver of pollinator population resilience in community-managed agroforestry systems. The subsequent section examines how the moderation of microclimates by enriched vegetation helps stabilize these ecological feedback loops.

3.4. Microclimatic Stability

Microclimatic monitoring revealed that plots with enriched vegetation exhibited lower daily temperature variance ($\sigma 2 \approx 1.8$ °C_2) than control plots ($\sigma 2 \approx 2.5$ °C_2). The daily fluctuation in relative humidity (max–min) was approximately 16% in the enriched plots, whereas it was around 22% in the control plots. Light intensity beneath the canopy decreased by approximately 15% in enriched plots relative to controls, indicating increased shading from the enriched vegetation (**Table 1**). Continuous monitoring of microclimatic conditions using HOBO MX2301 loggers demonstrated distinct differences between enriched and control plots throughout the observation period. As each plot was monitored with a single data logger, the reported values reflect overall plot conditions and may not fully capture small-scale spatial variations within each plot. On average, daytime temperature and light intensity were consistently lower under enriched vegetation, while relative humidity was higher and notably less variable from day to day. These trends illustrate the microclimatic buffering effect of vegetation enrichment, as evidenced in Table 1 by significant reductions in the CVs of temperature (-32 %) and humidity (-27 %) compared to the control. This moderation of the abiotic environment is consistent with the well-documented effects of vegetation structure on microclimate in tropical agroecosystems: canopy layering reduces direct solar exposure and wind, thereby mitigating near-surface thermal and vapor-pressure fluctuations (Reyes-González et al. 2020). The reduced midday light intensity (lux) in enriched plots indicates increased shading, which is known to stabilize humidity in leaf and air layers and reduce evapotranspiration (Montagini 2020; Theodorou et al. 2020). Such buffering has ecological significance for flower visitors, as it reduces nectar evaporation, pollen desiccation, and thermal stress, thereby extending safe foraging periods and enhancing reward quality (Bożek and Denisow 2023). Our behavioral findings align with this mechanism: increased and more consistent forager activity at hive entrances, along with larger brood areas and more honey storage, are anticipated outcomes when thermal and moisture stress are alleviated along foraging routes and within the immediate foraging landscape (Bentrup 2019; Heard 1999).

Table 1. Mean microclimatic conditions (± SE) and coefficient of variation (CV %) in enriched and control plots

Parameter (recorded by HOBO MX2301)	Unit	Enriched plots (Mean ± SE)	Control plots (Mean ± SE)	CV reduction (%)	*p*-value
Air temperature (Daytime)	°C	28.4 ± 0.6	30.1 ± 0.8	-32 %	< 0.05
Relative humidity	%	74.5 ± 2.1	69.2 ± 2.5	-27 %	< 0.05
Intensity of solar radiation (Noon average)	lux	27,800 ± 1 200	36,400 ± 1 700	-24 %	< 0.05
Wind speed (1 m height)	m s^{-1}	0.8 ± 0.1	1.1 ± 0.1	-18 %	n.s.

In stingless bees, even slight deviations from physiological thresholds can result in substantial impacts. Colonies typically curtail foraging when temperatures reach the low-to-mid 30°C range or relative humidity declines; prolonged exposure beyond these limits increases flight energy expenditure and diminishes recruitment efficiency (O'Connell et al. 2024). In our enriched plots, the average daytime temperature was approximately 1.7 °C lower, and the relative humidity was about 5% higher than in the control plots, with significantly reduced variability (**Table 1**). These differences are akin to the microclimatic alterations observed in shaded or diverse tropical systems, where such micro-buffers at the plot level enhance pollinator survival and activity (Baldock et al. 2019; Bożek and Denisow 2023). From a functional-restoration standpoint, this stabilization of abiotic factors acts as a support mechanism that amplifies the benefits of floral resource enrichment; it mitigates environmental variability along the trajectory from "more flowers" to "more effective foraging" to "stronger colonies" (Potts et al. 2016).

Two critical considerations should be acknowledged for a balanced interpretation. First, our light measurements were conducted in lux (photometric units) rather than photon units because lux is the standard output of the HOBO MX2301. While suitable for comparing relative shading, lux is less directly related to photosynthesis and nectar production processes than PAR/PPFD (Luo et al. 2020). Second, rainfall data were obtained from a nearby BMKG station; future research should incorporate on-site throughfall or soil moisture sensors to connect atmospheric moderation with plant-level water status and nectar dynamics. Despite this, the current early phase findings—cooler, moister, and more stable microclimates—correlate with the observed behavioral and colony-level improvements, reinforcing the conclusion that vegetation enrichment initiates a multi-layered recovery: floristic, faunal, and abiotic.

3.5. Implications for Ecosystem Function Recovery in Community Agroforestry

Overall, the findings on floral resources, pollinator activity, colony productivity, and microclimatic stability indicate that enhancing vegetation has a significant early impact on the pollination system in community-managed agroforestry. These results are consistent with the global consensus that enriched or diversified agroforestry systems serve as an effective strategy to enhance pollinator services and, consequently, ecosystem function. Notably, this study extends beyond structural restoration to demonstrate functional restoration, which involves reviving ecological processes (such as pollination and colony productivity) rather than merely the presence of plants. In the context of policy and community forestry, this functional perspective is crucial as it links restoration efforts to tangible services and potential livelihoods (such as honey production and crop pollination). This research directly addresses the gap identified in the Introduction by providing empirical evidence that vegetation enrichment can elicit measurable early functional responses in a community-managed agroforestry system. Specifically, we demonstrate that targeted enrichment results in coordinated enhancements in floral diversity, phenological overlap, pollinator foraging activity, colony productivity, and microclimatic stability within a short timeframe. These findings transcend structural restoration indicators by connecting vegetation interventions to functional pollination-related processes, offering one of the first integrated field-based demonstrations of early ecosystem function recovery under community agroforestry management. However, several limitations should be acknowledged. First, the monitoring period was brief (4 months) and only captured early responses; seasonal variation and long-term stability remain unknown. Second, we did not measure downstream crop pollination outcomes (fruit/seed set), which are necessary to demonstrate service recovery fully. Third, although the experimental design was well-structured, it involved a limited number of plots, potentially limiting broad extrapolation. These limitations are consistent with early-phase restoration research and indicate future research priorities (Hanafi et al. 2025; Kovács-Hostyánszki et al. 2017). Future work should extend monitoring to cover full flowering seasons, integrate sentinel crops for direct pollination service assessment, apply structural equation modeling to unravel causal pathways (enrichment → flower resources → pollinator activity → colony productivity → crop yield), and be replicated across multiple landscapes to enhance generalizability. This study provides an empirically grounded demonstration that vegetation enrichment in community agroforestry settings can stimulate early functional gains in pollinator systems. While evidence of full restoration is not yet available, the findings represent an important step toward bridging restoration ecology, agroforestry practice, and ecosystem service delivery.

4. Conclusions

This study underscores the significance of augmenting vegetation within communities as a catalyst for rapid ecological recovery in tropical agroforestry environments. The integration of diverse flowering plants into existing community spaces presents a viable strategy for restoring pollination functions and enhancing environmental stability. The observed transformations in vegetation, pollinator activity, colony health, and microclimate collectively demonstrate that small-scale ecological initiatives can enhance local ecosystem resilience when guided by participatory management approaches. Within 3 months of implementation, vegetation enrichment resulted in approximately 15% increases in floral diversity, 50% in flower density, and 64% in honey production compared to control plots. By linking these quantitative improvements to concurrent enhancements in pollinator foraging and colony productivity, this research contributes to the functional restoration paradigm by emphasizing process-based indicators of ecosystem recovery rather than solely structural vegetation characteristics. This finding highlights the potential of community-driven restoration methods to integrate ecological objectives with social and livelihood outcomes. Although these results represent an early stage of recovery, they establish a foundation for long-term strategies that align with biodiversity conservation and sustainable rural development. Expanding vegetation-enrichment efforts through local education, monitoring, and adaptive management is crucial to sustaining progress toward resilient, pollinator-friendly landscapes.

Acknowledgments

The authors gratefully acknowledge the Regent of Maros, the Tourism Office of Maros Regency, the Head of Pucak Village, the community of Pucak Village, and the Panrita Cani farmer group for their support, collaboration, and facilitation during the field activities. We also thank the Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Hasanuddin, for institutional and academic support. This article is an output of the Priority Research Downstreaming Program (Hilirisasi Riset Prioritas), Synergy Scheme, funded in 2025. We further acknowledge all individuals who contributed, directly or indirectly, to the successful completion of this study.

Author Contributions

A.M.: Conceptualization, Methodology, Data Curation, Writing, Original Draft Preparation; A.G.M.I.S: Data Analysis, Resources, Data Curation, Writing, Original Draft Preparation; Y.Y.: Investigation, Resources, Conceptualization, Data Curation, Writing, Review and Editing Methodology; F.F.R.: Formal Analysis, Investigation, Data Curation; S.D.R.: Data Curation, Writing, Review, Editing, Data Analysis; M.L., Investigation, Resources, Data Curation, Writing, Original Draft Preparation, Writing, Review & Editing; A.H.: Conceptualization, Methodology, Writing, Review and Editing.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI And AI-Assisted Technologies in the Manuscript Preparation

During the preparation of this work, the authors used Paperpal to edit and check grammar, as well as to search for references related to this manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

Agussalim, A., Umami, N., Nurliyani, and Agus, A. 2021. The Physicochemical Composition of Honey from Indonesian Stingless Bee *Tetragonula laeviceps*. *Biodiversitas* 22(6): 3257–3263. DOI: 10.13057/biodiv/d220639

Baldock, K. C. R., Goddard, M. A., Staniczenko, P. P. A., Vaughan, I. P., Hicks, D. M., Stone, G. N., Memmott, J., Morse, H., Osgathorpe, L. M., Scott, A. V., Robertson, K. M., Potts, S. G., Kunin, W. E., and Mitschunas, N. 2019. A Systems Approach Reveals Urban Pollinator

Hotspots and Conservation Opportunities. *Nature Ecology and Evolution* 3(3): 363–373. DOI: 10.1038/s41559-018-0769-y

Basari, N., Mohd Khairi, N., Aina S., and Ramli, S. N. 2018. Food Reward and Distance Influence the Foraging Pattern of Stingless Bee *Heterotrigona itama*. *Insects* 9(4): 138. DOI: 10.3390/insects9040138

Bentrup, G., Hopwood, J., Adamson, N. L., and Vaughan, M. 2019. Temperate Agroforestry Systems and Insect Pollinators: A Review. *Forests* 10(11): 981. DOI: 10.3390/f10110981

Bergamo, P. J., Sazima, M., Zambon, V., Streher, N. S., and Wolowski, M. 2021. Pollination Generalization and Reproductive Assurance by Selfing in a Tropical Montane Ecosystem. *The Science of Nature* 108(6): 1–6. DOI: 10.1007/s00114-021-01764-8

Bożek, M., and Denisow, B. 2023. Non-Forest Woody Vegetation: A Critical Resource for Pollinators in Agricultural Landscapes—A review. *Sustainability* 15(11): 8751. DOI: 10.3390/su15118751

Bonatti, M., González-Bermúdez, A., Rivera-Ferre, M. G., and Roy, M. 2024. Global Analysis of Social Learning's Archetypes in Natural Resource Management. *Humanities and Social Sciences Communications* 11: 1161. DOI: 10.1057/s41599-024-03590-5

Brooker, R. W., Schöb, C., Homulle, Z., Newton, A. C., George, T. S., Karley, A. J., and Pakeman, R. J. 2021. Facilitation and Biodiversity–Ecosystem Function Relationships in Crop Production Systems and Their Role in Sustainable Farming. *Journal of Ecology* 109(5): 2054–2067. DOI: 10.1111/1365-2745.13592

Buchori, D., Rizali, A., Priawandiputra, W., Raffiudin, R., Sartiami, D., Pujiastuti, Y., and Diniarsih, S. 2022. Beekeeping and Managed Bee Diversity in Indonesia: Perspective and Preference of Beekeepers. *Diversity* 14(1): 52. DOI: 10.3390/d14010052

Catarino, R., Bretagnolle, V., Perrot, T., Gaba, S., and Vialloux, F. 2019. Bee Pollination Outperforms Pesticides for Oilseed Crop Production and Profitability. *Proceedings of the Royal Society B: Biological Sciences* 286(1912): 20191550. DOI: 10.1098/rspb.2019.1550

Ciar, R. R., Bonto, L. S., Bayer, M. H., Rabajante, J. F., Lubag, S. P., Fajardo, A. C., and Cervancia, C. R. 2013. Foraging Behavior of Stingless Bees (*Tetragonula biroi*): Distance, Direction and Height of Preferred Food Source. *arXiv preprint arXiv* 1–32. DOI: 10.48550/arXiv.1310.3919

De Moraes, K. F., Gonçalves, G. S. R., Santos, M. P. D., De Oliveira, G. L., Gomes, L. B., and Lima, M. G. M. 2020. Climate Change and Bird Extinctions in the Amazon. *PLOS ONE* 15(7): e0236103. DOI: 10.1371/journal.pone.0236103

Diyaolu, C. O., and Folarin, I. O. 2024. The Role of Biodiversity in Agricultural Resilience: Protecting Ecosystem Services for Sustainable Food Production. *International Journal of Research Publication and Reviews* 5(10): 1560–1573. DOI: 10.55248/gengpi.5.1024.2741

Engel, M. S., Peggie, D., and Kahono, S. 2018. A Key to the Genera and Subgenera of Stingless Bees in Indonesia (Hymenoptera: Apidae). *Treubia* 45: 65–84. DOI: 10.14203/treubia.v45i0.3687

Gebremariam, H. G. 2024. A Systematic Review of Insect Decline and Discovery: Trends, Drivers, and Conservation Strategies Over the Past Two Decades. *Psyche: A Journal of Entomology* 1–16. DOI: 10.1155/2024/5998962

Hanafi, N., Hafizianor, H., Jauhari, A., and Hatta, G. M. 2025. Spatial Model of Carbon Stocks in Special Purpose Forest Area (KHDTK) Mungku Baru, Central Kalimantan Province, Indonesia. *Jurnal Sylva Lestari* 13(1): 159–172. DOI: 10.23960/jsl.v13i1.1066

Hartoyo, A. P. P., Satriawan, H., Madani, H. N., Setiajati, F., Rifana, H. Z., Wijayanto, A. K., Rahmawati, R., Siregar, U. J., and Karlinasari, L. 2025. Estimating Vegetation Density Dynamics, Tree Diversity, and Carbon Stock in the Agroforestry System of the Community Forest in Bogor Regency, Indonesia. *Jurnal Sylva Lestari* 13(1): 120–144. DOI: 10.23960/jsl.v13i1.989

Heard, T. A. 1999. The Role of Stingless Bees in Crop Pollination. *Annual Review of Entomology* 44(1): 183–206. DOI: 10.1146/annurev.ento.44.1.183

Hrncir, M., Barth, F. G., and Jarau, S. 2016. Stingless Bees (Meliponini): Senses and Behavior. *Journal of Comparative Physiology A* 202(9–10): 597–601. DOI: 10.1007/s00359-016-1117-9

IPBES. 2022. *Methodological Assessment Report on the Diverse Values and Valuation of Nature*. IPBES Secretariat. Bonn, Germany.

Kaluza, B. F., Wallace, H., Heard, T. A., Leonhardt, S. D., and Klein, A.-M. 2016. Urban Gardens Promote Bee Foraging Over Natural Habitats and Plantations. *Ecology and Evolution* 6(5): 1304–1316. DOI: 10.1002/ece3.1941

Kovács-Hostyánszki, A., Espindola, A., Vanbergen, A. J., Settele, J., Kremen, C., and Dicks, L. V. 2017. Ecological Intensification to Mitigate Impacts of Conventional Intensive Land Use on Pollinators and Pollination. *Ecology Letters* 20(5): 673–689.

Lau, P. W., Parys, K. A., Chakrabarti, P., Hung, K.-L. J., and Esquivel, I. L. 2023. The Nutritional Landscape in Agroecosystems: A Review on How Resources and Management Practices Can Shape Pollinator Health in Agricultural Environments. *Annals of the Entomological Society of America* 116(5): 261–275. DOI: 10.1093/aesa/saad023

León-Canul, R. A., Chalé-Dzul, J. B., Vargas-Díaz, A. A., Ortiz-Díaz, J. J., Durán-Escalante, K. C., Carrillo-Ávila, E., and Santillán-Fernández, A. 2023. Identification of Floral Resources Used by the Stingless Bee *Melipona beecheii* for Honey Production in Different Regions of Campeche, Mexico. *Diversity* 15(12): 1218. DOI: 10.3390/d15121218

Liang, H., Theodorou, P., Yang, C., and He, Y. 2023. The Effects of Urbanization on Pollinators and Pollination: A Meta-Analysis. *Ecology Letters* 26(9): 1629–1642. DOI: 10.1111/ele.14277

Lima, V. P., and Marchioro, C. A. 2021. Brazilian Stingless Bees are Threatened by Habitat Conversion and Climate Change. *Regional Environmental Change* 21(1): 10. DOI: 10.1007/s10113-021-01751-9

Luo, X., and Keenan, T. F. 2020. Global Evidence for the Acclimation of Ecosystem Photosynthesis to Light. *Nature Ecology and Evolution* 4(10): 1351–1357. DOI: 10.1038/s41559-020-1258-7

Main, A. R., Webb, E. B., Goyne, K. W., and Mengel, D. 2019. Reduced Species Richness of Native Bees in Field Margins Associated with Neonicotinoid Concentrations in Non-Target Soils. *Agriculture, Ecosystems and Environment* 287: 106693. DOI: 10.1016/j.agee.2019.106693

McIlwain, L., Cosens, B., Busumtwi-Sam, J., and Qun, L. 2024. Understanding the Complex Power Dynamics that Shape Collaborative Water Governance. *Ecology and Society* 29(3): 31. DOI: 10.5751/es-14740-290331

Montagnini, F. 2020. *The Contribution of Agroforestry to Restoration and Conservation: Biodiversity Islands in Degraded Landscapes*. Springer Nature.

Nath, R., Singh, H., and Mukherjee, S. 2022. Insect Pollinators Decline: An Emerging Concern of Anthropocene Epoch. *Journal of Apicultural Research* 62(1): 23–38. DOI: 10.1080/00218839.2022.2088931

Nicholson, C. C., and Egan, P. A. 2019. Natural Hazard Threats to Pollinators and Pollination. *Global Change Biology* 26(2): 380–391. DOI: 10.1111/gcb.14840

O'Connell, D. P., Baker, B. M., Atauri, D., and Jones, J. C. 2024. Increasing Temperature and Time in Glasshouses Increases Honey Bee Activity and Affects Internal Brood Conditions. *Journal of Insect Physiology* 155: 104635. DOI: 10.1016/j.jinsphys.2024.104635

Omer, E., Szlatenyi, D., Láng, V., Czako, I., Csenki, S., and Alrwashdeh, J. 2024. Farming Practice Variability and its Implications for Soil Health in Agriculture: A Review. *Agriculture* 14(12): 2114. DOI: 10.3390/agriculture14122114

Papa, G., Ambrogio, A., Karabagias, I. K., Aromolo, R., Plutino, M., Pignatti, G., Pellecchia, M., Maier, R., Lucarini, M., Bianchetto, E., Negri, I., and Durazzo, A. 2022. The Honey Bee *Apis mellifera*: An Insect at the Interface between Human and Ecosystem Health. *Biology* 11(2): 233. DOI: 10.3390/biology11020233

Potts, S., Imperatriz-Fonseca, V., Biesmeijer, J., Breeze, T., Dicks, L., Garibaldi, L., Ngo, H., Hill, R., Settele, J., and Vanbergen, A. 2016. Summary for Policymakers of the Thematic Assessment on Pollinators, Pollination and Food Production. *Biota Neotropica* 16(1). DOI: 10.1590/1676-0611201600010001

Quezada-Euán, J. J. G., Nates-Parra, G., Maués, M. M., Roubik, D. W., and Imperatriz-Fonseca, V. L. 2018. The Economic and Cultural Values of Stingless Bees (Hymenoptera: Meliponini) among Ethnic Groups of Tropical America. *Sociobiology* 65(4): 534. DOI: 10.13102/sociobiology.v65i4.3447

Reyes-González, A., Del-Val, E., Porter-Bolland, L., Camou-Guerrero, A., and Ramírez, M. I. 2020. Biocultural Diversity Loss: The Decline of Native Stingless Bees (Apidae: Meliponini) and Local Ecological Knowledge in Michoacán, Western México. *Human Ecology* 48(4): 411–422. DOI: 10.1007/s10745-020-00167-z

Roubik, D. W. (2022). Stingless bee (Apidae: Apinae: Meliponini) Ecology. *Annual Review of Entomology* 68(1): 231–256. DOI: 10.1146/annurev-ento-120120-103938

Roubik, D. W. 2023. *Ecology and Natural History of Tropical Bees*. University of Chicago Press. Chicago.

Suhri, A. G. M. I. 2025. Saving *Wallacetrigona incisa*: Community-led Conservation Integrating Science and Indigenous Knowledge in North Luwu's mountain forests, Indonesia. *Jurnal Sylva Lestari* 13(3): 692–711. DOI: 10.23960/jsl.v13i3.1165

Teuscher, M., Sundawati, L., Irawan, B., Buchori, D., Hölscher, D., Kreft, H., Ehbrecht, M., Gérard, A., Brose, U., Wollni, M., and Clough, Y. 2016. Experimental Biodiversity Enrichment in Oil-Palm-Dominated Landscapes in Indonesia. *Frontiers in Plant Science* 7(29): 1538. DOI: 10.3389/fpls.2016.01538

Theodorou, P., Murray, T. E., Paxton, R. J., Radzevičiūtė, R., Bleidorn, C., Grosse, I., Settele, J., Wubet, T., Schweiger, O., Lentendu, G., Kahnt, B., and Husemann, M. 2020. Urban Areas as Hotspots for Bees and Pollination but not a Panacea for All Insects. *Nature Communications* 11(1): 576. DOI: 10.1038/s41467-020-14496-6

Valido, A., Rodríguez-Rodríguez, M. C., and Jordano, P. 2019. Honeybees Disrupt the Structure and Functionality of Plant–Pollinator Networks. *Scientific Reports* 9(1): 4711. DOI: 10.1038/s41598-019-41271-5

Venjakob, C., Klein, A., Ebeling, A., Tscharntke, T., and Scherber, C. 2016. Plant Diversity Increases Spatio-Temporal Niche Complementarity in Plant–Pollinator Interactions. *Ecology and Evolution* 6(8): 2249–2261. DOI: 10.1002/ece3.2026

Velastegui-Montoya, A., Montalván-Burbano, N., Herrera-Franco, G., De Lima, A., and Peña-Villacreses, G. 2022. Land Use and Land Cover in Tropical Forest: Global Research. *Forests* 13(10): 1709. DOI: 10.3390/f13101709

Wongsa, K., Duangphakdee, O., and Rattanawannee, A. 2023. Pollination Efficacy of Stingless Bees, *Tetragonula pagdeni* Schwarz (Apidae: Meliponini), on Greenhouse Tomatoes (*Solanum lycopersicum* Linnaeus). *PeerJ* 11: e15367. DOI: 10.7717/peerj.15367

Yarnell, R. W., Mactavish, L. M., Phipps, W. L., Mactavish, D., Burgess, L. P., Harrison, S. W. R., Dell, S., Scott, D. M., and Ellis, J. A. 2013. The Influence of Large Predators on the Feeding Ecology of Two African Mesocarnivores: The Black-Backed Jackal and The Brown Hyaena. *South African Journal of Wildlife Research* 43(2): 155–166. DOI: 10.3957/056.043.0206