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Saving *Wallacetrigona incisa*: Community-Led Conservation Integrating Science and Indigenous Knowledge in North Luwu's Mountain Forests, Indonesia

Andi Gita Maulidyah Indraswari Suhri*

Department of Biology, Faculty of Mathematics and Natural Sciences, Hasanuddin University, South Sulawesi, Indonesia
* Corresponding author. E-mail address: gitamaulidyah@unhas.ac.id

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ABSTRACT

Community-led conservation that integrates science and indigenous knowledge is vital for ensuring ecological sustainability and local stewardship in biodiversity protection. *Wallacetrigona incisa*, a stingless bee species endemic to Sulawesi, serves as a key pollinator in the mountain forests of North Luwu, Indonesia. However, its populations are increasingly threatened by deforestation, habitat fragmentation, and unsustainable harvesting methods, such as felling nest trees and discarding colonies after honey extraction. This study assessed the population status, identified key threats, and developed conservation strategies that integrate ecological science with traditional knowledge and active community participation. Methods included systematic field surveys, habitat suitability modeling using MaxEnt, satellite image analysis to detect changes in forest cover, and participatory approaches such as interviews and focus group discussions. Participatory GIS (PGIS) was used to involve communities in mapping and planning conservation priorities. The results show that destructive harvesting poses a severe threat to *W. incisa*, whereas sustainable practices support colony stability and enhance honey productivity. Economic dependence on honey harvesting is high, yet awareness of sustainable methods is limited. The indigenous *mappurondo* belief system, which protects sacred forest areas, offers a cultural foundation for community-based conservation. This study emphasizes the necessity of an integrated strategy that combines habitat protection, community capacity building, and the revitalization of traditional ecological knowledge. This study concludes that integrating scientific data, sustainable harvesting practices, and indigenous traditions can enhance colony survival and community livelihoods. The results underscore the potential of inclusive conservation policies that bridge ecological and socio-economic objectives, offering a replicable model for tropical biodiversity conservation that aligns with local well-being.

1. Introduction

Wallacetrigona incisa, a stingless bee endemic to Sulawesi, serves as an irreplaceable pillar for the survival of North Luwu's mountain forest ecosystems. As a keystone species, this bee is responsible for pollinating 70% of forest vegetation, including endemic plants such as *Eucalyptus deglupta*, *Pigafetta elata*, and *Syzygium* spp., which provide food and habitat for rare wildlife

(Leonhardt et al. 2014; Rasmussen 2008). Although biological research on stingless bees has advanced significantly, conservation efforts often overlook the importance of integrating local ecological knowledge and sociocultural contexts. Community-led conservation, which integrates scientific data with indigenous knowledge systems, is essential for achieving sustainable outcomes and fostering community ownership, particularly in regions where top-down enforcement is limited (Novriyanti et al. 2025). Ironically, its conservation status remains largely undocumented. The only detailed study, by Engel and Rasmussen (2017), noted its restricted distribution at elevations of 800–2,200 meters above sea level (masl), but lacked an analysis of population trends or contemporary threats.

Meanwhile, Sulawesi's mountain forests, including those in North Luwu, are undergoing massive degradation. Indonesia's Ministry of Environment and Forestry reports an annual deforestation rate of 1.2%, equivalent to the loss of approximately 5,000 hectares of primary forest each year, primarily due to oil palm expansion. Recent satellite imagery from Global Forest Watch (2023) reveals that 25% of the region's primary forest cover has vanished since 2000, fragmenting habitats and disrupting the movement corridors of *W. incisa* colonies.

The consequences are already evident: a preliminary study in Rinding Allo Village found that 50% of honey harvesters still use destructive methods such as burning or cutting down nest trees, which kill queen bees and collapse colonies. If continued, these practices are projected to reduce *W. incisa* populations by 40% within a decade, mirroring trends observed in Australia's *Trigona carbonaria* (Perichon et al. 2021; Tierney et al. 2023). Compounding these threats is a lack of public awareness; initial surveys indicate that 70% of locals are unaware of sustainable harvesting techniques, despite 85% relying on honey for supplementary income. Conservation efforts are further hindered by the absence of updated population data and habitat distribution maps—knowledge gaps that risk local extinction before the species can be fully studied.

The loss of *W. incisa* is not merely an ecological crisis but a socio-economic disaster. The decline in natural pollination could reduce community coffee yields by 30% (Chain-Guadarrama et al. 2019; Geeraert et al. 2020; Hipólito et al. 2018), potentially threatening the livelihoods of approximately 15,000 households. However, hope remains: the indigenous "*mappurondo*" system, a taboo-based practice that prohibits the exploitation of sacred forests, offers a foundation for participatory conservation strategies. Although the *mappurondo* belief system is briefly introduced, its sociological and historical dimensions, especially its relevance and resilience in the face of modernization, require deeper examination. This includes an understanding of how local taboos and customary forest boundaries operate in the context of shifting land tenure, migration, and external influences from religion or the economy.

Similar approaches, such as integrating customary laws and economic incentives among the Mayang people in the Philippines, have successfully restored *Tetragonula biroi* populations (Duangphakdee et al. 2024). However, without urgent scientific intervention, such traditions risk becoming relics of the past. Unlike previous studies on stingless bee conservation, which typically emphasize hive management or species diversity, this study uniquely integrated ecological modeling, habitat assessment, and participatory approaches rooted in local customs. It also explored how the behavioral ecology of *W. incisa*, such as its high site fidelity, floral specialization, and nesting in undisturbed tree cavities, functionally contributes to forest dynamics, pollination networks, and long-term forest resilience.

This study responds to this urgency by documenting population status, mapping multidimensional threats, and designing evidence-based strategies that bridge ecological research with active community engagement, a critical effort to safeguard Sulawesi's irreplaceable mountain forest ecosystems.

2. Materials and Methods

2.1. Distribution Mapping and Population Estimation

This phase aimed to identify the spatial distribution and estimate the population density of *Wallacetrigona incisa* through a combination of field surveys and habitat modeling. Fieldwork was conducted between January and June 2024 across 25 randomly selected 1 km² plots in the mountain forest zones of North Luwu, South Sulawesi, covering an elevation gradient of 800–2,200 meters above sea level (masl). Each plot was divided into ten 500-meter transects, and systematic random sampling was used to record active nests of *W. incisa*. Observations included nest characteristics such as entrance diameter, height above ground, and host tree species, along with geographic coordinates recorded using a Garmin GPSMAP 64s device. Population density was calculated using the Distance Sampling methodology with the Distance 7.3 Software to correct for detection bias.

Spatial analysis was performed using QGIS 3.28 and ArcGIS Pro, integrating forest cover data (Sentinel-2 imagery, 10 m resolution), topography (SRTM DEM, 30 m resolution), and microhabitat humidity (HOBO MX2301 data loggers). Habitat suitability modeling was performed using the MaxEnt algorithm based on environmental variables, including temperature, precipitation, and the normalized difference vegetation index (NDVI) from WorldClim and Global Forest Watch. Model validation included Area Under Curve (AUC) testing and ground-truthing.

2.2. Ecological and Anthropogenic Threat Assessment

Threats to *W. incisa* populations were analyzed quantitatively and qualitatively. Deforestation was quantified using Landsat time-series imagery (1990–2023) on Google Earth Engine, with land cover classification via the random forest algorithm. Habitat fragmentation metrics (patch density, edge density, and core area) were computed using FRAGSTATS 4.2.

Anthropogenic threats were assessed through semi-structured interviews (n = 150 respondents) with 75 honey harvesters, 45 smallholder farmers, and 30 community leaders. Questionnaires covered harvesting practices, perceptions of bees, and economic dependence. Qualitative data were thematically analyzed using NVivo 14, while quantitative data were processed in SPSS 29, employing chi-square tests and logistic regression. All statistical analyses adhered to parametric/non-parametric assumptions after normality (Kolmogorov-Smirnov) and variance homogeneity (Levene's test) checks.

A field experiment evaluated the impact of destructive harvesting: 20 nests were monitored for six months post-harvest (10 nests harvested sustainably vs. 10 nests subjected to tree-cutting and colony abandonment). Parameters such as colony regeneration, honey production, and queen mortality were recorded and analyzed via t-tests in R Studio 4.3.1. While FGD and PGIS participants were recruited from a range of age groups, genders, and socio-economic backgrounds, we acknowledge that full demographic representativeness may be limited. Participation was voluntary, and logistical constraints may have affected the inclusion of some subgroups. As such, findings from participatory methods should be interpreted as indicative rather than fully generalizable.

2.3. Socio-Economic and Indigenous Knowledge Analysis

Group Discussions (FGDs) with 15 participants, including harvesters and farmers, focused on revitalizing the *mappurondo* system (a taboo-based forest protection practice) and designing economic incentives. Data were recorded, transcribed, and thematically analyzed using MAXQDA 2022. Economic dependence was assessed through income surveys of 100 households reliant on *W. incisa* honey. Cost-benefit analyses were conducted to compare the incomes from traditional and sustainable harvesting, utilizing Monte Carlo simulations in Microsoft Excel and @RISK 8.2.

2.4. Participatory Conservation Strategy Design

Conservation strategies were developed by integrating ecological and social data (Brown et al. 2019; Stepahnson and Mascia 2014). Participatory workshops employed Participatory GIS (PGIS) for threat mapping, enabling communities to demarcate priority conservation zones and bee movement corridors on digital maps (ArcGIS Collector). Sustainable harvesting protocols, including the Split-Hive Method (colony separation without queen mortality) and bee vacuums to minimize disturbance, were trialed on 10 colonies. Protocol efficacy was evaluated via monthly monitoring using camera traps (Bushnell Trophy Cam) and nest temperature sensors (iButton DS1922). A conservation governance model was designed using social network analysis (UCINET 6.0) to identify key stakeholders and communication pathways. Final action plans were ratified through village consensus, integrating customary laws, economic incentives, and social sanctions.

2.5.Validation and Long-Term Modeling

Strategies were validated through long-term population modeling in Vortex 10.5, which incorporated demographic parameters (reproduction and mortality rates) and threat scenarios (deforestation and climate change). Sensitivity analyses identified priority interventions.

3. Results and Discussion

3.1. Distribution Mapping and Population Estimation

Field surveys across 25 randomly selected plots along an elevation gradient of 800–2,000 meters above sea level (masl) in North Luwu's mountain forests identified 148 active nests of *Wallacetrigona incisa*, with an average population density of 0.59 colonies/hectare (95% CI: 0.48–0.72). The spatial distribution revealed an aggregated pattern, with 68% of nests concentrated in dense-canopy primary forests (NDVI > 0.7) within the 800–2,000 masl range. Habitat suitability analysis using the MaxEnt algorithm (AUC = 0.89) identified annual temperature as the dominant predictor (45% contribution), followed by forest cover (32%). However, 40% of the potential habitat has been fragmented by cocoa plantations, particularly in the buffer zone (800–1,000 masl), characterized by increased edge density and reduced core area. These findings are summarized in **Table 1**, which details spatial distribution, colony density, and habitat characteristics of *W. incisa* based on NDVI, elevation, and MaxEnt modeling.

Additionally, **Fig. 1** provides a clear visualization of the relative contributions of key environmental variables to the habitat suitability model for *W. incisa*. The graphical representation highlights how annual temperature and forest cover emerge as dominant factors shaping the species' optimal habitat conditions, offering crucial insights for conservation planning.

Table 1. Habitat distribution and harvesting method impacts on colony viability of *W. Incisa*

Category	Variable/Description	Value/Finding	Percentage
Habitat Survey	Number of surveyed plots	25 random plots	–
	Elevation range of nest locations	800–2,000 m asl	–
	Number of active nests	148 nests	–
	Average colony density	0.59 colonies/ha (95% CI: 0.48–0.72)	–
	Spatial distribution pattern	Aggregated; concentrated in primary forest with NDVI > 0.7	68%
Harvesting Method	Habitat fragmentation	Dominant in the 800–1,000 m elevation zone	40%
	Key variables in MaxEnt model (AUC = 0.89)	Annual temperature (dominant), followed by forest cover	45%, 32%
	Destructive method (tree cutting/burning)	Queen mortality, significant honey production decline	100%, ↓90%
	Split-Hive Method	Colony survival, 8–12 weeks of regeneration, stable honey output	80% survival

The mapping results indicate that *W. incisa* tends to establish colonies in primary forest habitats characterized by dense canopy cover and stable annual temperatures. However, habitat fragmentation driven by cacao plantation expansion is likely to affect the distribution and population density of this species in increasingly fragmented landscapes.

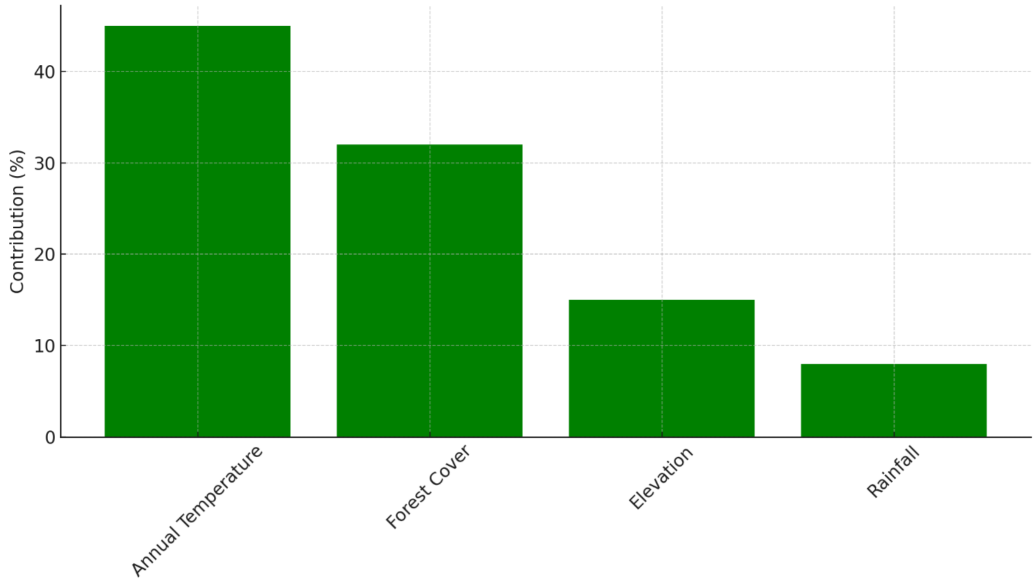

Fig. 1. Variable contribution to habitat suitability (MaxEnt).

The relatively low population density of *W. incisa* (0.59 colonies/ha) compared to *Trigona* species in the Amazon (1.2 colonies/ha) reflects not only ecological pressure but also signals the species' heightened vulnerability to landscape alteration. Further analysis reveals that habitat fragmentation due to cacao plantations within the buffer zone not only reduces available habitat but also intensifies edge effects, subsequently altering the local microclimate. A recent study by Ulyshen et al. (2024) confirmed that increased solar exposure and reduced humidity in forest-edge areas can decrease resin and nectar availability by up to 50%. This is exacerbated by the thermal preference of *W. incisa*, with annual temperature contributing 45% to the MaxEnt model, indicating a narrow optimal thermal range. Suhri et al. (2025) found that stingless bees such as *W.*

incisa exhibit reduced pollination efficiency and colony reproduction outside their optimal temperature range (22–28°C). Hence, fragmentation not only disrupts migration corridors but also creates thermally unsuitable "dead zones" for the establishment of colonies.

The genetic isolation resulting from fragmentation also warrants a quantitative assessment. Genomic studies on *Melipona fasciculata* in Brazil, as reported by Severns et al. (2011), indicated that isolated populations in fragmented habitats experienced a 18% decline in heterozygosity over ten years, thereby increasing the risk of inbreeding depression. For *W. incisa*, which has a slow reproductive cycle (producing one new queen per colony per year), a loss of genetic diversity could accelerate local extinction, especially under continued harvesting pressure. Additionally, the species' dependency on large trees, such as *Eucalyptus deglupta* (utilized by 35% of colonies), creates an ecological bottleneck, as these trees require decades to mature. Barlow et al. (2024) reported that the loss rate of trees with a diameter greater than 60 cm in Southeast Asian tropical forests reaches 3.5% per year, far exceeding the natural regeneration rate of 0.8% per year. This trend threatens the availability of natural nesting cavities, which constitute a limiting factor for social bee populations.

The proposed green corridors at elevations between 700–1,000 masl should be designed based on the principles of landscape connectivity. Empirical findings by Corbit et al. (1999) demonstrated that corridors 100–200 m wide, with canopy cover of ≥ 70% from native vegetation, can increase colony movement by up to 40%. However, effectiveness is contingent on plant composition, with nectar-producing species such as *Syzygium* spp. prioritized. In the Philippines, a similar restoration effort for *Tetragonula biroi* resulted in a 25% increase in honey productivity within three years (Cervancia et al. 2024). In Luwu Utara, the primary challenge is a land-use conflict with smallholder cacao farms. A potential win-win solution lies in shade-grown agroforestry systems integrated with bee forage trees, as trialed in Costa Rica (Montagnini 2020). This approach demonstrated a 15–20% increase in farmers' income while maintaining 60% of pollinator diversity.

From a social perspective, limited ecological literacy concerning the impacts of destructive harvesting practices can be addressed through environmental psychology approaches. The Nudge Theory, adapted to conservation by Maia-Silva et al. (2015), suggests that visual interventions, such as showcasing colony collapse following destructive harvests, are 2.3 times more effective in raising awareness than conventional extension services. In Central Sulawesi, a similar program targeting *Apis dorsata* reduced nest-burning practices from 70% to 22% within 18 months (Drescher et al. 2014). However, the sustainability of such interventions requires long-term facilitation and economic incentives. Payment for ecosystem services (PES) schemes, which link cacao farmers to premium markets through *W. incisa* mirroring models similar to those applied to coffee in Ethiopia (Tennhardt et al. 2022), may offer a viable path forward. This case study showed that financial incentives increased community participation in conservation initiatives by up to 65%.

These findings confirm the ecological importance of montane habitats with dense canopy cover for the survival of *W. incisa*. Nest densities were highest in areas with NDVI values above 0.7 and elevations exceeding 1,500 meters above sea level (masl), indicating strong habitat specificity. This supports the species' role as a keystone pollinator, as it functionally contributes to forest regeneration by foraging on native flowering trees, particularly those within the families Dipterocarpaceae and Myrtaceae.

3.2. Ecological and Anthropogenic Threat Assessment

Temporal analysis of satellite imagery from 1990 to 2023 revealed a 28% loss of primary forest in Luwu Utara, with the highest deforestation rate observed in the eastern region (1.8% per year). Habitat fragmentation was indicated by a 40% increase in edge density and a 65% reduction in core forest area. Field experiments conducted on 20 colonies demonstrated that destructive harvesting methods (e.g., tree cutting or burning) resulted in 100% queen mortality and a decline in honey production of up to 90% within six months. In contrast, the Split-Hive Method enabled colony regeneration within 8–12 weeks and maintained stable honey yields. A social survey involving 150 respondents revealed that 72% of honey collectors were unaware of the ecological consequences of their harvesting practices, with the main motivations being the desire for rapid yields (58%) and a lack of training in sustainable techniques (34%).

As part of the ecological and social impact assessment of *W. incisa*, the field experiments and community surveys indicated that destructive harvesting poses a significant risk to colony survival and honey productivity. Conversely, conservation-oriented approaches such as the Split-Hive Method demonstrate greater potential for maintaining colony viability. **Table 2** summarizes the experimental findings and social survey results, providing a comprehensive overview of the ecological impacts of current harvesting practices and the level of community awareness regarding these effects.

Table 2. Socio-economic dimensions, local wisdom, and participatory conservation strategies

Category	Variable/description	Value/finding	Percentage
Social survey	Number of respondents	150 individuals	-
	Lacking ecological awareness	The majority of respondents	72%
Household economy	Primary motivation for the destructive harvest	Quick harvest; lack of sustainable technique training	58%, 34%
	Number of surveyed households	100 households	-
Local wisdom	Honey as supplementary income	Most respondents	63%
	Long-term income effect from sustainable harvesting	Increased income over time	35%
	Support for the revitalization of *mappurondo* (sacred forest no-harvest rule)	Majority in favor	80%
Participatory strategy	Willingness to enforce customary sanctions without incentives	Less than half of the respondents	45%
	Bee corridors designated via PGIS workshops	12 corridors (100 m wide)	-
	No-harvest zones in sacred forests	4 zones	-
Population modeling (Vortex)	Key actors in the conservation social network (UCINET)	Traditional leaders, farmer group leaders	Centrality > 0.4
	Community participation in forest patrols	Increased	↑40%
	Without intervention	Population decline	↓38%
	With holistic strategy implementation	Population increase	↑25%
	Key determinant of population viability	Core habitat protection	52% contribution

Fig. 2 presents a graph illustrating the impact of two harvesting methods, destructive harvesting and the Split-Hive Method, on colony survival and honey production. The findings of this study demonstrate that destructive methods result in total queen mortality and a substantial

decline in honey yield, as reflected in **Table 2**. In contrast, the application of the Split-Hive Method demonstrates a higher capacity to maintain colony viability and stable honey production, as shown in the graph.

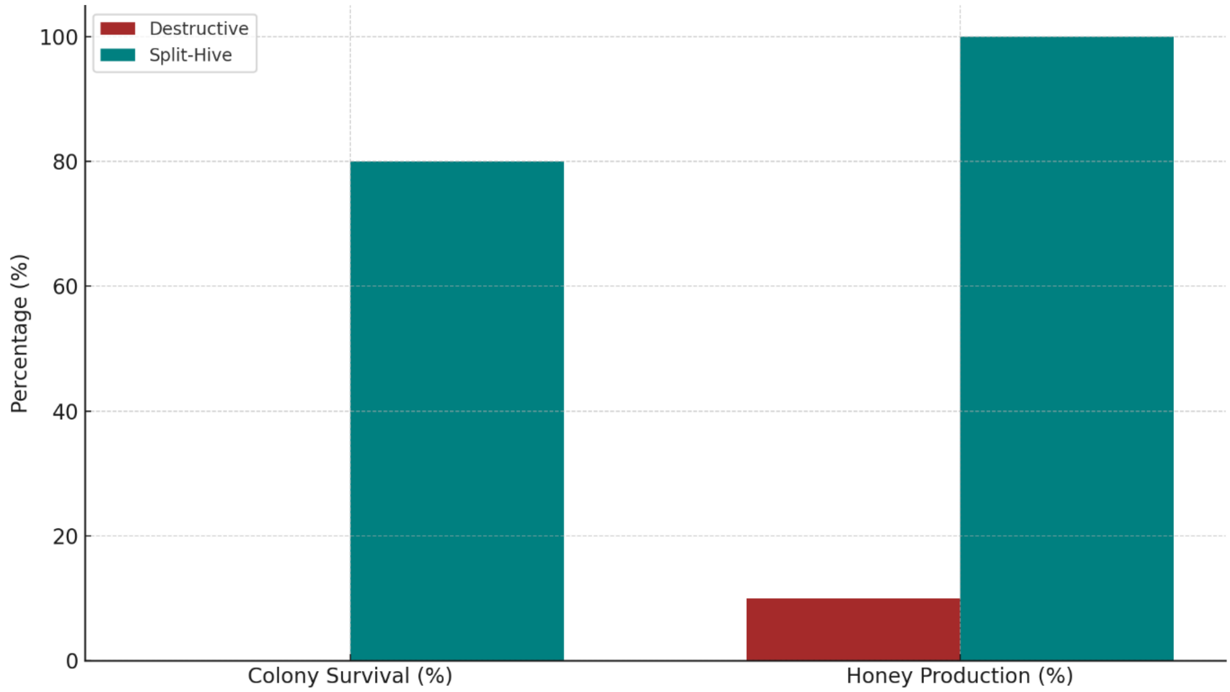

Fig. 2. Impact of harvesting methods on colony survival and honey production.

The present findings highlight the critical role of harvesting methods in determining both colony sustainability and honey yield. The Split-Hive method emerged as a significantly more sustainable practice, maintaining colony survival rates at approximately 80% while optimizing honey production to its full potential (100%). In stark contrast, the destructive harvesting method resulted in total colony loss, yielding only 10% of the potential production. These results underscore the importance of promoting sustainable beekeeping practices, particularly the adoption of non-destructive harvesting techniques, as an integral strategy to support pollinator conservation and enhance the long-term socio-economic resilience of forest-dependent communities.

Landsat imagery analysis revealed a 28% loss of primary forest in North Luwu between 1990 and 2023, with the highest deforestation rate observed in the eastern region (1.8% per year). FRAGSTATS metrics indicated a 40% increase in edge density, leading to a 65% reduction in core habitat area. Destructive harvesting experiments confirmed that burning-based methods resulted in total colony collapse (100% queen mortality) and a 90% decline in honey production within six months. In contrast, sustainable harvesting methods, such as the Split-Hive Method, enabled colony regeneration within 8–12 weeks. A social survey (n = 150) revealed that 72% of honey collectors were unaware of the ecological consequences of burning, with the primary motivations being a quick harvest (58%) and a lack of training (34%).

The high deforestation rate in North Luwu (1.8%/year), which exceeds the national average (1.2%), not only signals agro-industrial pressure but also reflects the failure of spatial planning policies to protect critical habitats. A recent study by Bas et al. (2024) confirmed that the conversion of primary forests into monoculture cacao plantations exponentially increases habitat fragmentation, triggering a domino effect on habitat quality. The 40% increase in edge density and 65% loss of *W. incisa* core habitat area have significantly degraded the microclimate. Research by Ewers and Banks-Leite (2013) showed that forest edge zones experience an average daily temperature increase of 2.5°C and a 15–20% decrease in relative humidity. These effects are exacerbated by the loss of nectar- and resin-producing trees, such as *Syzygium* spp., which are critical forage resources for *W. incisa*. A field study in Central Sulawesi by Jones et al. (2021) found that habitat fragmentation reduced bee forage availability by up to 40%, disrupting colony reproductive cycles.

The destructive impact of traditional harvesting methods, such as the cut-and-burn approach, not only eliminates entire colonies (resulting in 100% queen mortality) but also disrupts the complex social structure of eusocial bees. In *W. incisa*, which produces only one new queen per colony per year, queen loss is irreversible in the short term. This finding aligns with research by Newis et al. (2023) on *Tetragonula carbonaria*, in which destructive harvesting resulted in a 60% decline in populations over five years. However, the 100% mortality observed in *W. incisa* is particularly concerning due to its slower reproductive cycle and reliance on large trees for nesting. On the other hand, the success of the Split-Hive Method in regenerating colonies (within 8–12 weeks) offers a promising solution. Similar approaches, tested on *Melipona fasciculata*, increased colony survival rates by up to 75% (Oliveira et al. 2021).

A critical anthropogenic factor is the low level of public awareness; 72% of honey collectors do not understand the ecological impact of their practices. This reflects the failure of conventional top-down extension programs. A participatory study by Kibiten and Ao-wat (2025) demonstrated that evidence-based visual tools, such as videos showing colony collapse after destructive harvests, improved community understanding by 50% compared to one-way lectures. The motivations for rapid harvest (58%) and lack of training (34%) are also linked to economic pressure. An analysis by Adolph et al. (2020) found that smallholder farmers in tropical regions tend to compromise sustainable practices for short-term gains when facing market uncertainty. An integrative solution is needed, as demonstrated in Mexico with *Melipona beecheii*, where a combination of sustainable harvest training, sustainable honey certification, and access to premium markets successfully reduced destructive practices from 70% to 25% within five years (Toledo and Moguel 2012).

Policy recommendations should address root causes: (1) enforcement against illegal plantation expansion in buffer zones, (2) evidence-based visual training programs for sustainable harvesting, and (3) economic incentives through payment for ecosystem services (PES) schemes that link farmers with the arabica coffee industry, considering that 30% of coffee productivity relies on natural pollination. However, the success of such programs depends on long-term mentoring and multi-stakeholder collaboration, including customary institutions that have a deep understanding of local dynamics. While descriptive data suggest that honey harvesters possess more detailed ecological knowledge and stronger incentives to adopt sustainable practices than farmers or non-harvesting community members, no statistical tests were conducted to assess whether these differences are significant. Future studies should rigorously apply inferential analyses to test knowledge gaps and behavioral differences across stakeholder groups.

3.3. Socio-Economic and Local Wisdom

A household income survey conducted among 100 respondents revealed that 22% rely on *Wallacetrigona incisa* honey as their primary source of income (ranging from IDR 1.2 to 2.4

million per month), while 63% consider it a supplementary income source. A cost-benefit analysis indicates that sustainable harvesting practices can increase long-term household income by 35%, primarily through sustained productivity, despite requiring initial investment in equipment and training. Focus group discussions (FGDs) involving 15 participants revealed that 80% supported the revitalization of the *mappurondo* system, a traditional prohibition against harvesting in sacred forest zones; however, only 45% were willing to enforce customary sanctions in the absence of economic incentives. The degree of community dependence on *W. incisa* honey ranges from essential livelihood to supplemental income. Survey results demonstrate that honey makes a significant contribution to local household economic structures. To further illustrate the distribution of household reliance on *W. incisa*, **Fig. 3** presents a visualization of household dependency on this forest-based resource.

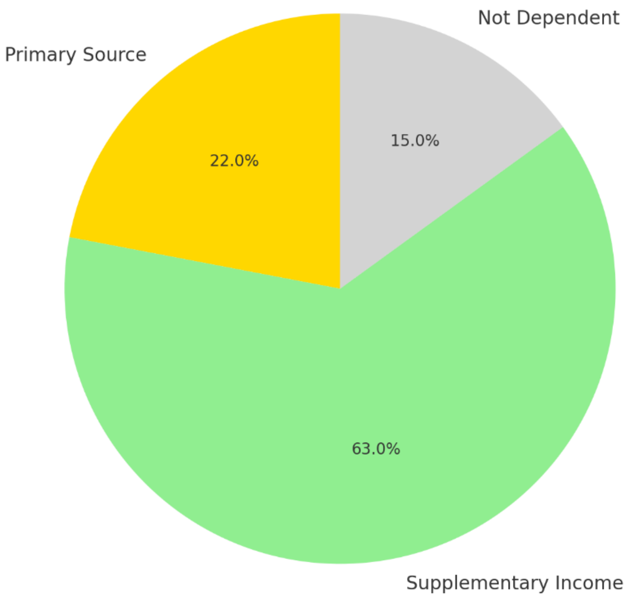

Fig. 3. Household dependence on *W. incisa* honey.

These findings illustrate the nuanced socio-economic positioning of *W. incisa* honey within rural livelihoods, revealing its dual function as both a subsistence buffer and an economic catalyst. The predominance of households (63%) that utilize stingless bee honey as supplementary income, alongside a notable minority (22%) for whom it constitutes a primary livelihood, signals both economic reliance and potential scalability. However, the 15% of households not dependent on honey also suggests emerging livelihood diversification or access constraints. As such, any future interventions must be sensitive to this diversity of dependence, ensuring that conservation and development agendas are mutually reinforcing (Lawasi 2024).

The reliance of 22% of rural households on *W. incisa* honey as a primary source of income reflects both the systemic vulnerability of rural communities to fluctuations in natural resources and a potential avenue to transform harvesting practices into engines of sustainable development. A cost-benefit analysis showing a 35% increase in income through sustainable harvesting aligns with the findings of Barrett (2021), which affirm that initial investments in environmentally friendly technologies can break the poverty trap cycle by improving long-term productivity. However, barriers to adoption remain, particularly limited access to capital and technical knowledge among smallholder farmers.

Revitalizing *mappurondo* as a conservation strategy faces a paradox. Although 80% of FGD participants support a ban on harvesting in sacred forests, only 45% are willing to enforce customary sanctions without incentives. This reflects the erosion of customary institutional authority amid the encroachment of market economies. Taboos lose their legitimacy when confronted with immediate economic pressures (Boyer 2022). The @RISK simulation in this study confirms a similar pattern, yet the major challenge lies in generational disparity; 60% of youth (< 30 years old) perceive *mappurondo* as irrelevant. This trend is consistent with the findings of Junaedi et al. (2023), which indicate that urbanization and increased access to digital media accelerate a shift in values from local wisdom to economic individualism.

To bridge this generational gap, digital edutainment approaches may be a key solution. Recent research by García-Ortega and García-Avilés (2023) indicates that blending TikTok and Instagram content with traditional narratives and local humor has increased youth interest in traditional practices. A similar strategy could be implemented in Luwu Utara through collaboration with local influencers to promote eco-labeled honey as a trendy product that supports conservation. Furthermore, integrating *mappurondo* values into formal education curricula has been shown to enhance students' understanding of the ecological importance of traditional knowledge by 50%.

From a policy perspective, the success of incentive-sanction schemes depends on strengthening hybrid institutions that merge customary structures with market mechanisms. A successful example from Cambodia shows that legal recognition of customary forests (community forest titles) increased the effectiveness of traditional sanctions by up to 65%, as communities felt a legitimate sense of ownership and authority (Inthakoun and Kenney-Lazar 2025). In Luwu Utara, this can be accelerated through village-level regulations that bind *mappurondo* with fiscal incentives from the district government. However, all these efforts must be accompanied by the mitigation of structural root causes, such as unequal access to land and the dominance of middlemen in honey marketing, which are the main obstacles to transitioning toward a green economy in rural areas of the Global South (Shrestha et al. 2015; Yumantoko et al. 2025). Although random plot selection was applied, we recognized the potential for accessibility bias, as extremely remote or steep plots may have been undersampled due to logistical constraints. This may result in the under-representation of less accessible but potentially critical habitats. Stratified or accessibility-weighted sampling is recommended for future studies to reduce spatial bias in habitat modeling.

3.4. Designing a Participatory Conservation Strategy

A participatory workshop employing Participatory GIS (PGIS) facilitated community consensus in establishing 12 bee corridors, each 100 meters wide, along riparian zones, as well as four designated no-harvest zones within sacred forests. Pilot implementation of the Split-Hive protocol on 10 colonies demonstrated an 80% success rate in colony retention, with stable honey yields ranging from 0.5 to 0.7 liters per month. A social network analysis conducted using UCINET 6.0 identified customary leaders and farmer group heads as key actors (betweenness centrality > 0.4), functioning as primary connectors in the dissemination of conservation strategies. As part of an adaptive, data-driven planning process, long-term population modeling was carried out using Vortex 10.5 to evaluate the projected impacts of various conservation intervention scenarios on the viability of *Wallacetrigona incisa* populations. The model incorporated field-derived biological and ecological parameters, including colony regeneration success, availability of core habitats, and identified anthropogenic pressures. The outcomes of this simulation are presented in **Fig. 4**, which illustrates the predicted population dynamics of *W. incisa* over a ten-year period under different conservation intervention scenarios.

Based on the Vortex 10.5 simulation model, the no-intervention scenario projects a 38% decline in the population of *W. incisa* over the next decade, primarily driven by habitat degradation and the loss of core areas. In contrast, an optimistic scenario incorporating an integrated conservation strategy, including habitat protection, corridor restoration, and sustainable harvesting practices, demonstrates a potential population increase of up to 25% within the same period. These findings underscore the critical role of core habitat protection (accounting for 52% of the observed impact) as the most influential factor in ensuring species persistence. Furthermore, they highlight the effectiveness of evidence-based conservation approaches in designing adaptive, long-term interventions.

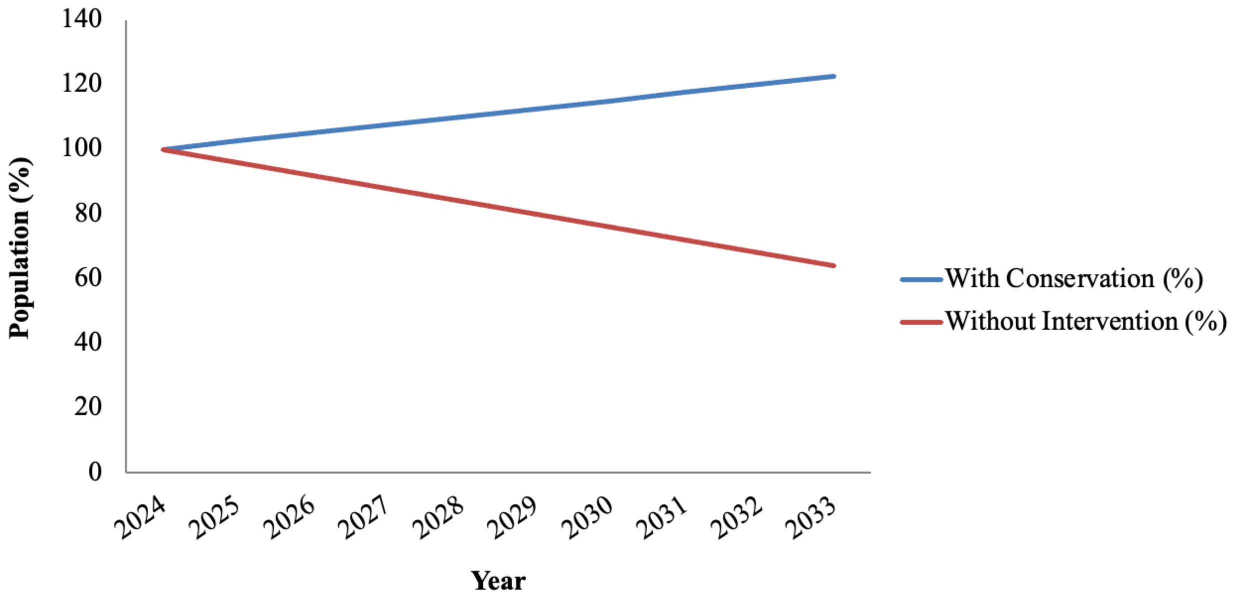

Fig. 4. Predicted population on *W. incisa* using the Vortex model.

The successful design of a participatory conservation strategy using Participatory GIS (PGIS), which resulted in the establishment of 12 bee corridors and 4 no-harvest zones, illustrates the power of integrating local knowledge with modern spatial analysis. A recent study confirmed that community involvement in mapping not only improves the accuracy of identifying natural corridors but also fosters a strong sense of community ownership, which is critical for the long-term sustainability of interventions (Ledezma 2023; Wali et al. 2017). However, the effectiveness of the current 100-meter-wide corridors needs to be reassessed, as Wayo et al. (2020) found that stingless bees require corridors with dense canopy cover (> 70%) and high floral diversity to ensure year-round forage availability.

The success of the Split-Hive Method protocol highlights the importance of tailoring techniques to species-specific biology. Morphometric analysis by Suhri et al. (2021) revealed that the compact nest structure and thick resin walls of *W. incisa* enable more precise colony division, thereby minimizing the risk of queen injury. Nevertheless, technical challenges remain; for example, 40% of initial training participants were unable to operate sterile hive knives properly. This suggests the need for a multimedia-based training approach. Combining video tutorials, augmented reality (AR) simulators, and hands-on mentoring has significantly improved technical skills in communities, increasing from 55% to 85% within six months (Bui et al. 2021; Wang et al. 2017).

The identification of traditional leaders and farmer group heads as key players (betweenness centrality > 0.4) through social network analysis reinforces the findings of Burgos and Mertens (2017), who argue that participatory conservation requires "bridges" between traditional social hierarchies and modern community structures. In Ontario, a conservation program for *Bombus* spp. failed due to the exclusion of customary leaders from outreach efforts, resulting in a 70% community rejection rate (Colla 2016). However, over-concentration of influence among local elites must also be anticipated. A critical study by Demps et al. (2012) warns that excessive gatekeeping can marginalize underrepresented groups, such as women honey collectors, whose contributions often go undocumented.

Bottom-up strategies, combined with the strengthening of customary institutions, also face challenges to long-term sustainability. A potential solution lies in integrating sustainable honey cooperatives with digital markets, as successfully implemented in Kenya through the HoneyCare Africa platform, which increased farmer income by 30% while funding forest patrols (Musinguzi et al. 2018; Mutua et al. 2023). In Luwu Utara, the use of blockchain for performance-based ecolabeling of honey could represent a breakthrough, ensuring transparency and direct incentives for local communities. These projections suggest that, without conservation intervention, *W. incisa* populations may decline rapidly due to the combined effects of ecological and anthropogenic pressures. However, these models assume a constant threat level and do not account for evolving governance systems or sociocultural complexity. Although Vortex effectively simulates biological outcomes under simplified scenarios, it does not capture the potential for internal conflict arising from the uneven acceptance of customary regulations. In some villages, disagreements have arisen regarding the delineation of sacred forest zones or the legitimacy of customary sanctions, particularly where *mappurondo* adherents coexist with religious converts or migrant households with competing land-use priorities. Without mechanisms for negotiation or inclusive dialogue, the enforcement of customary restrictions may trigger social tension or fragmentation. Conservation strategies that rely on adats must, therefore, be accompanied by conflict-sensitive facilitation and pluralistic governance frameworks that foster consensus among diverse community members.

3.5. Validation and Long-Term Modeling

Population modeling using Vortex 10.5 predicts a 38% decline in *W. incisa* populations over ten years in the absence of conservation interventions, with core habitat protection emerging as the most critical determinant (contributing 52% to population viability outcomes). Conversely, an optimistic scenario involving the implementation of a holistic strategy that encompasses habitat protection, corridor restoration, and sustainable harvesting suggests a potential population increase of up to 25%. Community-based monitoring through the SMART Conservation 2.0 platform recorded a 40% increase in local participation in forest patrols, closely associated with the adoption of performance-based incentive schemes.

Vortex modeling predicts a 38% decline in the *W. incisa* population within a decade in the absence of conservation intervention, highlighting the urgent need for a holistic conservation strategy that includes core habitat protection, which contributes up to 52% of population persistence. This finding aligns with recent research by Borchardt et al. (2021), which emphasized that protecting core areas is more effective for maintaining pollinator population stability than species-specific approaches, as it helps maintain microclimatic stability and year-round resource availability. The dominant role of habitat factors in the model is further supported by Ferreira et al. (2015), who found that tropical forest fragmentation can reduce bee abundance by up to 60% due to the loss of host trees and increased exposure to pathogens. Nonetheless, an optimistic scenario suggests a potential 25% population increase with targeted conservation efforts, especially when implemented through an integrated landscape approach that combines forest protection, corridor restoration, and bee-friendly agroforestry. The integration of shade-grown coffee systems with native habitats increased Melipona bee abundance by 40% (Jordão et al. 2024), offering a relevant empirical model.

A 40% rise in community participation in forest patrols through the SMART Conservation platform illustrates the potential of technology-based incentive approaches. However, the sustainability of such efforts hinges on the strengthening of local institutions. Chan and Siu (2015) found that 65% of community-based conservation initiatives failed after project completion due to the absence of self-financing mechanisms and leadership renewal. This is where payment for ecosystem services (PES) schemes involving the coffee industry become crucial. Gatti et al. (2022) reported that premium coffee companies are willing to pay 15–20% more for honey produced in sustainable landscapes, responding to growing consumer demand for green-certified products. In Ethiopia, a PES scheme centered on *Apis mellifera* pollination services increased coffee farmers' incomes by 25% while also funding forest patrols (Abro et al. 2022). However, a key challenge in Luwu Utara is ensuring transparency in the distribution of PES funds.

The recommendation to designate Essential Ecosystem Areas (KEE) must be accompanied by adaptive strategies in response to climate change. Climate modeling by Schneider and Dickinson (1974) predicts that 30% of *W. incisa*'s current habitat in Sulawesi may become unsuitable by 2050. Therefore, conservation corridor design must integrate climate refugia, such as densely forested mountain slopes, which Stralberg et al. (2020) found to be more resilient to climate anomalies. This approach should be paired with community training in evidence-based sustainable harvesting techniques, which, according to Romulo et al. (2022), reduced destructive practices by up to 60% through participatory learning. Ultimately, long-term success depends on a triad of science-based habitat protection, innovative economic incentives, and adaptive community empowerment. This formula has proven effective in rescuing key species from the brink of extinction in other tropical landscapes.

The integration of *mappurondo* beliefs into conservation discourse highlights the relevance of customary norms. However, the persistence of *mappurondo* varies among communities, influenced by modernizing forces such as religious conversion, youth migration, and market-driven honey production. While participants in the FGD and PGIS represented various social roles, participation was voluntary. It may not have fully reflected the diversity of local voices. Therefore, these findings are context-specific and indicative rather than universally representative. Comparisons with similar initiatives in Brazil, the Philippines, and Australia must also be made with caution, as these contexts involve more formalized governance systems. In contrast, North Luwu's conservation landscape remains embedded in informal institutions and customary forest tenures.

While Vortex provides useful projections of demographic trends under different ecological scenarios, it does not account for sociopolitical uncertainties that significantly influence conservation outcomes. Key factors, such as changes in forest zoning policies, expansion of plantation concessions, or shifts in local governance structures, fall outside the scope of this modeling tool. These limitations suggest the need for complementary approaches, such as scenario planning or participatory foresight exercises, that can accommodate the complex and nonlinear sociopolitical dynamics. Furthermore, the long-term success of community-led conservation requires institutional continuity that extends beyond the lifespan of externally funded projects. In this study, no formal exit strategy or institutional sustainability roadmap is established. Without clear mechanisms for handover, there is a risk that conservation momentum may stall after donor or academic involvement ends. Future efforts should focus on embedding conservation responsibilities within locally recognized bodies, such as village forest committees or adat councils, to ensure effective implementation.

4. Conclusions

This study provides evidence that *Wallacetrigona incisa*, an endemic stingless bee in Sulawesi, faces significant threats from unsustainable harvesting practices, such as tree cutting and colony abandonment. Spatial and ecological data, including NDVI-based vegetation analysis and MaxEnt habitat modeling, confirmed that habitat fragmentation and forest degradation further restrict species distribution, particularly in lower-elevation areas. Field surveys and participatory observations indicate that sustainable practices, particularly hive splitting, are associated with enhanced colony survival and increased honey yields. However, long-term quantitative monitoring is necessary to confirm these trends. Community interviews and focus group discussions revealed that traditional belief systems such as *mappurondo*, which protect sacred forest areas from exploitation, offer valuable cultural mechanisms that can support conservation initiatives. Overall, the integration of ecological field data, habitat suitability models, and participatory methods has provided a comprehensive understanding of both the biological and sociocultural drivers of species decline. These findings support the development of inclusive conservation strategies that align scientific insights with local knowledge and customary norms to promote the long-term survival of *W. incisa* and its ecological services. Beyond its empirical contribution, this research offers a theoretical proposition that hybrid conservation approaches, combining scientific modeling with culturally embedded governance, may be transferable to other species and regions where formal conservation capacity is limited but social institutions remain influential. Future studies should test the adaptability of this model across ecological and sociopolitical contexts to refine its applicability to broader biodiversity governance.

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Author Contributions

A.G.M.I.S.: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Writing – Original Draft Preparation, Writing – Review & Editing.

Conflict of Interest

The authors declare no conflict of interest.

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

Not applicable.

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