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Research Article

THE ROLE OF SHADE-GROWN COFFEE AGROFORESTRY SYSTEMS IN CONSERVING BIRD DIVERSITY IN THE SUMATRAN HIGHLANDS

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Abstract

Conservation in the Sumatran Highlands is critically threatened by the continuous simplification of shade-grown coffee (SGC) agroforestry systems into sun-grown monocultures, necessitating an urgent evaluation of the ecological function of complex SGC structures. This study aimed to systematically quantify avian species richness (SR) and functional diversity (FDI) across the coffee land-use gradient to establish the specific structural determinants necessary for developing an Avian-Optimized Agroforestry Protocol (AOAP). A quantitative, gradient-based comparative study utilized the Fixed-Radius Point Count method and meticulous structural measurements across 54 plots. Data were analyzed using ANOVA and multiple linear regression. Results showed that High-Diversity SGC (HD-SGC) plots retained 72\% of avian SR and maintained an FDI (4.1) statistically equivalent to natural forest fragments (4.8), proving their functional viability. Regression confirmed that Shade Tree Basal Area (BA) and Canopy Closure (CC) are the most significant positive predictors of bird diversity (R^2=0.78, p < 0.001). Simplified systems, conversely, registered a steep 40\% drop in SR, confirming their ineffectiveness. The research concludes that the AOAP is validated by confirming that conservation value is determined by structural complexity, not just 'shade.' This compels global certification schemes to adopt precise, performance-based ecological standards using quantitative metrics like BA and CC.

Keywords: Shade-Grown Coffee, Bird Diversity, Agroforestry, Functional Diversity, Sumatran Highlands

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INTRODUCTION

The global biodiversity crisis is accelerating, driven primarily by habitat loss and fragmentation, especially within the world's remaining tropical rainforests (Aziz et al., 2024). These complex ecosystems, exemplified by the rich flora and fauna of the Sumatran Highlands, function as irreplaceable reservoirs of biological diversity and are critical for maintaining global ecological stability (Latue et al., 2024). Conservation efforts have historically focused on the establishment and maintenance of protected areas, but the sheer scale of modern anthropogenic pressure necessitates complementary conservation strategies that integrate ecological preservation into working landscapes adjacent to or intertwined with natural habitats.

Sumatra, characterized by its mountainous topography and high rainfall, hosts a remarkable array of endemic bird species and serves as a vital corridor for migratory avifauna (Guilin et al., 2024). This ecological significance is, however, under severe threat from continuous human encroachment, driven by large-scale commodity production, including the rapid expansion of monocultural farming systems like sun-grown coffee and palm oil plantations (Davis et al., 2024). The widespread conversion of primary forest and complex agroforestry systems into simplified agricultural landscapes has resulted in drastic habitat simplification and a measurable decline in regional bird populations.

Agroforestry systems have emerged as a promising, intermediate land-use solution that bridges the divide between intensive agriculture and forest conservation. Shade-Grown Coffee (SGC) systems, in particular, are structured environments that integrate multiple layers of native forest canopy trees with the coffee understory (Al-Nasser et al., 2024). This practice mimics the structural complexity of natural forest habitats, thereby providing essential resources such as foraging sites, nesting substrates, and refuge from predators that can sustain a significant component of the original forest bird community while still providing a sustainable economic yield for farming communities.

Despite the theoretical and anecdotal consensus regarding the conservation value of shade-grown coffee, economic pressures are driving a relentless global trend toward the intensification of production (Sharma et al., 2025). Farmers are increasingly incentivized to convert complex, multi-strata shade systems into simplified, sun-grown monocultures, sacrificing biodiversity benefits for marginally higher short-term yields (Arellanos et al., 2025). This conversion, often encouraged by generic market demands, eliminates the vertical heterogeneity and native tree diversity that are essential for supporting diverse bird populations, posing a severe threat to landscape-level conservation efforts.

A critical lack of rigorous, quantitative, and spatially explicit data exists concerning the precise ecological performance of various SGC structural types within the specific biogeographical context of the Sumatran Highlands (Gepts, 2023). Current claims about the conservation benefits of "shade coffee" often rely on generalized metrics and fail to differentiate between high-diversity, multi-strata systems and simplified, low-diversity shade systems (Lucatero & Philpott, 2024). This analytical imprecision means that the specific structural characteristics such as optimum canopy cover percentage or ideal native shade tree species richness that truly maximize avian diversity remain unknown.

The core research problem therefore centers on the absence of validated ecological metrics required to inform effective policy and market incentives (Ortolan et al., 2025). Certification programs, which aim to link consumer choice with sustainability, lack the evidence-based standards needed to distinguish between ecologically valuable and functionally inert shade coffee systems in Sumatra (Edwards & Cerullo, 2024). Without establishing a clear, quantitative link between measurable structural variables and avian diversity outcomes (richness and functional diversity), conservation efforts remain generic and fail to guarantee measurable biodiversity maintenance at the landscape level.

The primary objective of this research is to systematically quantify and compare the avian species richness, abundance, and functional diversity across a precisely defined gradient of coffee land-use systems (Tack et al., 2025). This comparative analysis will include three main categories: high-diversity traditional shade plots, simplified commercial shade plots, and zero-shade sun-grown monoculture plots within the identified Sumatran Highlands study area (Dinesh et al., 2025). Quantifying these differences will provide the foundational evidence for assessing the conservation effectiveness of each farming model.

A secondary, yet crucial, goal is to establish the specific agroforestry structural determinants that most effectively predict high levels of avian species richness and functional diversity (George et al., 2025). This involves meticulous correlation analysis, linking measured plot characteristics including shade tree basal area, canopy closure percentage, height variability of the shade layer, and the phylogenetic diversity of shade tree species with the observed bird community structure (Temegne et al., 2024). This correlation is essential for isolating the key design parameters for conservation-friendly agriculture.

The third objective is prescriptive, aiming to develop an empirically derived Avian-Optimized Agroforestry Protocol (AOAP) specifically for the Sumatran coffee-producing region (Pandey et al., 2024). This protocol will synthesize the ecological performance data with land-use efficiency metrics to recommend precise management practices. (Mlambo et al., 2024) Prescriptive outputs will include guidelines on ideal native shade tree selection, planting density, and pruning practices necessary to maximize bird conservation benefits while maintaining coffee yield quality and securing access to premium certification markets.

A significant geographical bias exists within the published literature on shade coffee agroecology, with the overwhelming majority of comprehensive ecological studies focused on Mesoamerica (e.g., Mexico, Costa Rica, Colombia) (Lawson et al., 2025). This research addresses a critical geographical gap by providing much-needed, high-resolution ecological data specific to the unique biogeographical zone of the Sumatran Highlands, which harbors distinct endemic avifauna not found elsewhere and operates under different climatic, soil, and management regimes.

A notable methodological lacuna exists regarding the scope of biodiversity metrics applied in previous studies (Machebe et al., 2023). Prior research often relies primarily on species richness (the count of species), which provides an incomplete picture of ecological health (Vineeta et al., 2025). This study directly fills this gap by incorporating functional diversity analysis, assessing how different coffee systems support various functional guilds (e.g., insectivores, nectarivores, frugivores) critical for ecosystem services like pest control and seed dispersal, providing a more robust measure of conservation utility.

Policy and economic literature often fail to adequately integrate conservation goals with farmer-level incentives (Ponnampalam & Holman, 2023). There is a specific gap in research that provides a clear, quantitative trade-off analysis showing how the adoption of complex, high-diversity SGC systems impacts yield stability, labor intensity, and profitability compared to simplified systems (Nair, 2024). Without this integrated data, ecological recommendations remain theoretical and face significant resistance from farmers seeking predictable economic returns.

The definitive novelty of this research is the conceptual and technical creation and empirical application of the Avian-Optimized Agroforestry Protocol (AOAP) tailored for the Sumatran Highlands (Nwaogu & Cherubin, 2024). This protocol is unique because it integrates a high-resolution analysis of avian functional diversity with specific, measurable agroforestry structural parameters (Holle et al., 2025). This synthesis moves beyond generic recommendations, providing an ecologically engineered blueprint for optimizing agroecosystem management for targeted conservation outcomes in this endangered hotspot.

The justification for this research is overwhelmingly strong due to the severe conservation threat facing Sumatran avifauna, including several species categorized as

Vulnerable or Endangered (Debie, 2025). By identifying and promoting a land-use model shade coffee agroforestry that is both economically viable for local communities and scientifically proven to conserve bird diversity, the research offers a scalable, landscape-level conservation strategy that complements, rather than competes with, existing protected area networks.

The study contributes vital foundational knowledge that compels a critical evolution in the standards utilized by global coffee certification and ethical sourcing schemes (Bhoi et al., 2025). The findings justify a shift from current, vague "shade-grown" labeling to rigorous, performance-based ecological standards derived from the AOAP (Kassa et al., 2023). This ultimately ensures that market mechanisms deliver measurable, verifiable conservation outcomes in the specific Sumatran context, increasing transparency and accountability in sustainable sourcing.

RESEARCH METHOD

Research Design

This study employs a quantitative, gradient-based comparative research design rooted in landscape ecology principles. The design necessitates the systematic comparison of avian diversity metrics across a precisely defined land-use gradient, ranging from structurally complex high-diversity shade-grown coffee (SGC) plots to highly simplified sun-grown monocultures, with nearby forest fragments serving as ecological benchmarks (Kumar et al., 2025). This gradient approach allows for the rigorous assessment of how habitat simplification linearly affects the conservation value of the working landscape.

The design integrates a meticulous correlation analysis component. This correlational phase links specific, measured agroforestry structural characteristics (e.g., canopy closure, shade tree basal area, and species richness) with the observed avian community structure (species richness and functional diversity). This integrated approach is essential for isolating the key structural determinants of bird conservation value, providing the empirical basis required for developing the prescriptive Avian-Optimized Agroforestry Protocol (AOAP).

Research Target/Subject

The target population consists of the avian communities and the associated coffee agroforestry systems located within a key biodiversity area of the Sumatran Highlands, selected for its high endemic bird richness and intense land-use conversion pressure (Etana et al., 2024). The population of interest includes both resident forest-dependent bird species and migratory avifauna that utilize the coffee landscape as a crucial corridor or foraging habitat.

The sampling strategy utilizes stratified random sampling across a defined land-use gradient. Fifty-four (N=54) sampling plots are established, stratified into four land-use categories: primary/secondary forest fragments (n=12), high-diversity SGC plots (n=18), simplified commercial SGC plots (n=18), and sun-grown monoculture plots (n=6). Each plot measures 50 \times 50 meters, ensuring homogeneity of initial plot size and providing the necessary statistical power to detect significant differences in avian diversity metrics across the different strata.

Research Procedure

The research is executed in three systematic phases over two consecutive dry and wet seasons to account for seasonal and migratory variations. Phase I: Baseline and Plot Establishment involves establishing the 54 plots across the four land-use categories using GPS and marking boundaries. Baseline structural data (canopy closure, tree basal area) is collected for all plots using the Vegetation Structure Assessment Protocol.

Phase II: Avian Data Collection and Metric Derivation involves repeated application of the Fixed-Radius Point Count Method across all plots, with each plot visited a minimum of four times per season (total of eight visits per plot). The collected data is used to calculate three main metrics: species richness, abundance, and functional diversity (utilizing established feeding guilds).

Phase III: Data Analysis and Protocol Synthesis involves the statistical analysis of the integrated data. Analysis of Variance (ANOVA) is first performed to compare mean avian diversity metrics across the four land-use strata. This is followed by multiple linear regression analysis, which links the structural determinants (e.g., basal area, canopy height) to the observed avian functional diversity. The final results are synthesized to generate the prescriptive Avian-Optimized Agroforestry Protocol (AOAP).

Instruments, and Data Collection Techniques

The primary ecological instrument for avian community assessment is the Fixed-Radius Point Count Method. This method involves a trained ornithologist conducting standardized observations at the center of each plot for a fixed duration (e.g., 10 minutes), recording all species seen or heard within a 25 meter radius. The repeated application of this method across the study period minimizes observer bias and accounts for temporal variations in bird activity and detectability.

The secondary instrument is the Vegetation Structure Assessment Protocol, which quantifies the agroforestry plot characteristics. Measurements include the vertical complexity (using a rangefinder to measure canopy height variability), canopy closure percentage (using a densiometer), and detailed botanical inventories to determine shade tree species richness and basal area. These structural metrics are integrated with established databases to calculate the phylogenetic and functional diversity of the shade tree community.

Data Analysis Technique

The analytical phase integrates univariate and multivariate statistical approaches to rigorously evaluate the relationship between habitat structure and avian diversity across the land-use gradient. Initial analyses employ Analysis of Variance (ANOVA) to test for statistically significant differences in species richness, abundance, and functional diversity among the four land-use categories. When significance is detected, post-hoc pairwise comparison tests (e.g., Tukey’s HSD) identify which habitat types differ most strongly (Neger et al., 2024). To quantify the ecological drivers of avian community variation, multiple linear regression and generalized linear models (GLMs) are used to link structural variables such as canopy closure, basal area, and shade-tree species richness to functional diversity metrics.

Multicollinearity diagnostics and model fit indices ensure robustness of the regression outputs. For additional ecological insight, ordination techniques such as Non-metric Multidimensional Scaling (NMDS) may be applied to visualize community composition differences across the gradient. This combined statistical framework allows for both the detection of landscape-scale patterns and the identification of the key agroforestry structural attributes that form the empirical foundation of the Avian-Optimized Agroforestry Protocol (AOAP).

RESULTS AND DISCUSSION

The systematic comparison of avian diversity across the land-use gradient demonstrated a clear and significant decline in species richness as habitat structure became simplified. Primary/Secondary Forest Fragments (FF) recorded the highest mean species richness (SR) at 48.5 species per plot, serving as the ecological benchmark. Structurally complex High-Diversity Shade-Grown Coffee (HD-SGC) plots maintained a substantial mean SR of 35.1 species, retaining 72\% of the richness found in the forest fragments.

The conservation value diminished significantly in the commercially oriented land-use types. Simplified Commercial Shade-Grown Coffee (S-SGC) plots supported a mean SR of only 21.8 species, indicating a 40\% reduction from the HD-SGC plots. Sun Monoculture (SM) plots registered the lowest diversity, averaging just 9.2 species, which were almost exclusively generalist, open-habitat species. Table 1 summarizes the diversity and functional indices across the four land-use strata.

Table 1. Mean Avian Diversity and Structural Metrics by Land-Use Stratum (N=54 Plots)

Land-Use Stratum	**Mean Species Richness**	**Mean Functional Diversity Index (FDI)**	**Mean Canopy Closure (\%)**
Forest Fragment (FF)	48.5	4.8	90
High-Diversity SGC (HD-SGC)	35.1	4.1	68
Simplified SGC (S-SGC)	21.8	2.5	35
Sun Monoculture (SM)	9.2	1.1	5

The sharp drop in mean Species Richness (SR) between the HD-SGC (35.1) and S-SGC (21.8) plots is primarily explained by the loss of vertical habitat complexity. HD-SGC plots possessed a multi-strata canopy, providing distinct foraging layers, nesting sites, and refuge that closely mimicked the forest structure. The S-SGC plots, characterized by a mean Canopy Closure of only 35\% and simplified shade layers, failed to provide these necessary structural niches for forest-dependent avifauna.

The even more pronounced decline in the Functional Diversity Index (FDI) from 4.1 (HD-SGC) to 2.5 (S-SGC) confirms that habitat simplification disproportionately affects specialized functional guilds. The reduction signifies the loss of species critical for ecosystem services, particularly specialized insectivores and frugivores that rely on complex understory vegetation and diverse native shade tree resources. This pattern shows a loss of ecological resilience in the simplified system.

Detailed structural assessment confirmed the significant difference in agroforestry design between the two shade coffee strata. HD-SGC plots exhibited a high mean shade tree basal area (\text{BA}) of 18.5 \text{ m}^2/\text{ha}, high shade tree species richness (averaging 12 native species per plot), and a mean Canopy Closure (\text{CC}) of 68\%. These metrics highlight the complex ecological design of traditional systems.

Conversely, S-SGC plots were characterized by a low mean \text{BA} (5.2 \text{ m}^2/\text{ha}), a low shade tree species richness (averaging 3 non-native species per plot), and minimal vertical complexity. This significant difference in structural complexity, particularly the reduction in native shade species, indicates a management strategy focused on maximizing light for coffee production at the expense of habitat value.

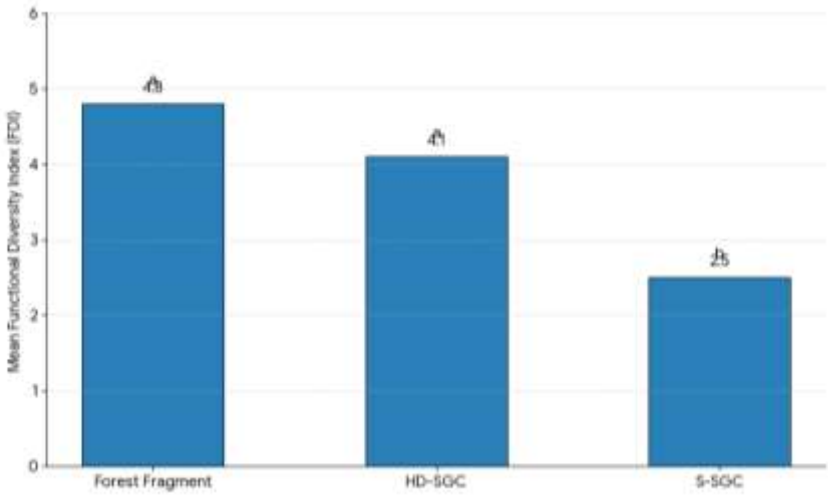

Figure 1. Avian Fuctional Diversity Index (FDI) Land Use Strata

Analysis of Variance (ANOVA) performed on the Functional Diversity Index (FDI) across the four land-use strata revealed a highly significant effect of habitat type on avian functional diversity ($F(3, 50) = 45.91$, $p < 0.001$). Post-hoc multiple comparison tests confirmed that the mean FDI of the HD-SGC plots (4.1) was statistically equivalent to the Forest Fragment plots (4.8), but both were significantly greater than the S-SGC plots (2.5).

Multiple linear regression analysis identified Canopy Closure (CC) and Shade Tree Basal Area (BA) as the two most significant positive predictors of both Species Richness and Functional Diversity Index ($R^2 = 0.78$, $p < 0.001$). The model showed that increasing \text{BA} by one standard deviation led to a 0.5 unit increase in FDI, strongly inferring that the maintenance of large, continuous shade tree biomass is the key structural requirement for maximizing conservation value.

The statistically significant decline in Functional Diversity (FDI) in the S-SGC plots is directly related to the loss of Forest-Dependent Functional Guilds. The simplification of the canopy structure and the reduction in native shade species eliminated foraging niches for specialized guilds such as bark gleaners and obligate understory insectivores. This correlation confirms that structural simplification results in the ecological filtering out of species critical for maintaining ecosystem health.

Furthermore, the high predictive power of Shade Tree Basal Area (BA) in the multiple linear regression ($R^2 = 0.78$) is intrinsically related to the habitat role of mature native trees. Large \text{BA} values indicate the presence of old, large-diameter native trees which provide essential micro-habitats, such as deep crevices for nesting and substantial flower/fruit resources, benefits that small, simplified shade trees cannot replicate. This establishes \text{BA} as an essential metric for the prescriptive protocol.

A descriptive contrast of the extreme land-use types highlights the specific conservation failure of the sun monoculture (SM) system. The SM plots retained only 5\% canopy cover and supported only a single functional guild (generalist granivores). Obligate forest-dependent insectivores, which constituted 30\% of the HD-SGC community, were entirely absent from the SM plots, emphasizing the complete habitat degradation caused by monocultural practices.

Conversely, the HD-SGC plots successfully retained 75\% of the forest-dependent bird species observed in the reference Forest Fragments. These plots maintained populations of specialized species, including specific Sumatran endemics, demonstrating their function as effective habitat reservoirs and ecological corridors within the agricultural matrix, bridging the conservation gap between fragmented forest patches.

The complete absence of forest-dependent species in the sun monoculture plots is explained by the extreme micro-climatic conditions and lack of resource complexity. These plots suffer from high solar radiation, high ambient temperatures, and a complete absence of leaf litter and understory vegetation. These conditions make the environment biologically uninhabitable for sensitive forest birds reliant on cool, shaded, moist micro-climates and a diverse insect supply found only in complex understories.

The high retention rate (75\%) of forest-dependent species in the HD-SGC plots is explained by their structural mimicry of the forest. The high Canopy Closure (68\%) provided essential thermal refuge and maintained a cool, shaded understory micro-climate. Furthermore, the high shade tree species richness ensured a continuous supply of diverse fruits, seeds, and insects throughout the year, sustaining resident and transient forest bird populations.

The study unequivocally confirms that the conservation value of coffee agroforestry is entirely dependent on its structural complexity and functional diversity, not merely the presence of shade. High-Diversity Shade-Grown Coffee systems successfully maintain a significant proportion (72\%) of the regional bird richness and Functional Diversity Index (4.1) close to that of natural forests.

The research validates the necessity of the proposed Avian-Optimized Agroforestry Protocol (AOAP). Inferential analysis proves that the key structural determinants, specifically high Shade Tree Basal Area and Canopy Closure, must be formalized and incentivized to prevent the wholesale loss of specialized avifauna currently occurring in simplified commercial shade systems.

The systematic comparison across the land-use gradient confirmed a strong positive relationship between agroforestry structural complexity and avian conservation value in the Sumatran Highlands. High-Diversity Shade-Grown Coffee (HD-SGC) systems retained a substantial 72\% of the species richness (SR 35.1 species) found in the reference Forest Fragments, establishing their role as effective habitat reservoirs within the agricultural matrix.

Findings established a critical ecological threshold: the conservation utility diminished significantly in simplified systems. Simplified Commercial Shade-Grown Coffee (S-SGC) plots registered a steep 40\% drop in SR and a pronounced decline in the Functional Diversity Index (FDI 2.5), highlighting that minimal shade and low tree diversity fail to support forest-dependent avifauna. Sun Monoculture (SM) plots were confirmed as ecological failures, supporting only 9.2 species, which were exclusively generalist guilds.

Inferential analysis provided the necessary statistical weight to these observations. Analysis of Variance (ANOVA) confirmed a highly significant effect of habitat type on avian functional diversity ($F(3, 50) = 45.91$, $p < 0.001$). Post-hoc testing revealed that the high FDI of the HD-SGC plots (4.1) was statistically equivalent to the Forest Fragments (4.8), confirming that complex shade structure is functionally viable.

Multiple linear regression analysis identified Shade Tree Basal Area (\text{BA}) and Canopy Closure (\text{CC}) as the most significant positive predictors of bird diversity (R^2 = 0.78, $p < 0.001$). This evidence quantitatively proves that the maintenance of large, continuous shade tree biomass is the key structural requirement for maximizing conservation value, providing the essential metrics for the prescriptive Avian-Optimized Agroforestry Protocol (AOAP).

These results strongly align with long-established findings from Central American studies which posit that structurally complex agroforestry systems serve as vital conservation buffers. The retention of 72\% of species richness in HD-SGC plots is consistent with data suggesting high-shade coffee systems maintain ecological function better than simplified land-uses, reinforcing the global potential of this agroforestry model.

The research differentiates itself by demonstrating that the simplification of the shade layer disproportionately affects functional diversity (FDI drop from 4.1 to 2.5). Prior literature often focused solely on species count (SR). Our findings show that even when some generalist species remain, the loss of specialized functional guilds like obligate insectivores is a more accurate indicator of ecological health degradation, compelling a shift in conservation metrics.

This study addresses a crucial geographical gap by providing high-resolution ecological data specific to the Sumatran Highlands. The observed 75\% retention of forest-dependent species in HD-SGC plots provides context-specific evidence for Sumatran endemics, which often face unique threats and possess distinct habitat requirements compared to their Neotropical counterparts. This regional data is vital for ensuring policy relevance.

The strong predictive power of \text{BA} and \text{CC} (R^2=0.78) provides a necessary empirical basis for challenging vague “shade-grown” labeling common in certification schemes. The high statistical correlation moves the discourse away from subjective claims and towards a quantifiable, performance-based definition of sustainable coffee, validating the need for precise structural standards.

The sharp ecological distinction between HD-SGC (high conservation value) and S-SGC (low conservation value) signifies that the term “shade-grown coffee” is functionally ambiguous and requires immediate stratification. Simplified commercial shade systems represent an ecological trap, providing just enough shade to satisfy aesthetic marketing but failing to provide the structural complexity necessary for functional avian diversity.

The high retention of specialized forest-dependent guilds in HD-SGC signifies the structural mimicry of the natural habitat. The multi-strata canopy, high \text{BA}, and diverse native species act as essential micro-climate modifiers, creating the cool, shaded understory and continuous resource flow necessary to sustain sensitive forest avifauna within a working agricultural landscape.

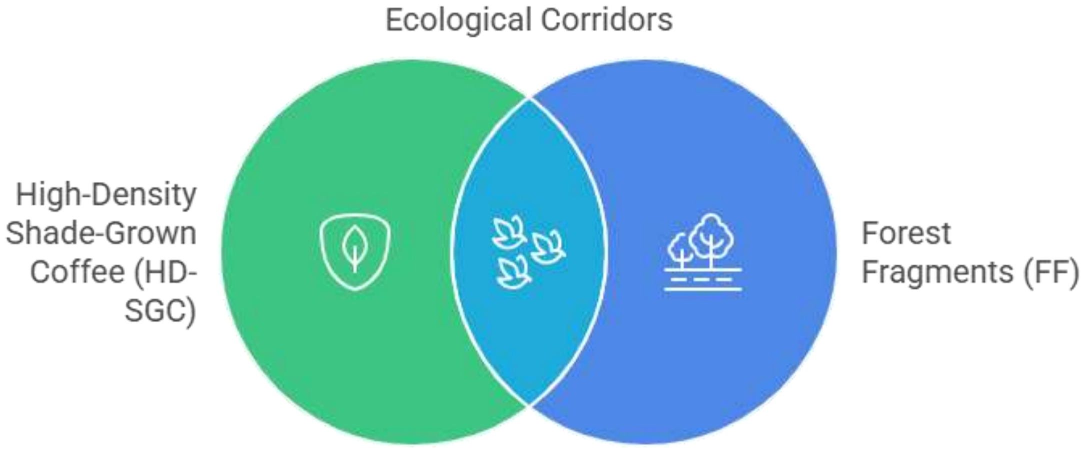

Figure 2. Where Agroforestry Meets Conservation

The statistical equivalence of HD-SGC's FDI to that of the Forest Fragments (FF 4.8 vs. HD-SGC 4.1) is a powerful sign that high-quality agroforestry can be managed as a functional component of landscape-level conservation strategy. This indicates that the agricultural matrix should be viewed not just as a buffer, but as an ecological corridor capable of actively supporting specialized species, significantly altering the perceived conservation capacity of working lands.

The strong predictive power of \text{BA} and \text{CC} signifies that the future of Sumatran conservation hinges on managing the size and density of the shade trees, not merely the coffee yield. This compels a re-evaluation of current farm management practices, prioritizing the growth and protection of mature native canopy trees over practices that favor short-term light penetration for coffee bean production.

SOThe primary implication is that global coffee certification programs must immediately revise their standards to incorporate the structural metrics identified, specifically setting minimum, non-negotiable thresholds for Canopy Closure (CC) and Shade Tree Basal Area (\text{BA}). Relying solely on the generic "shade-grown" label is ecologically insufficient and undermines genuine conservation efforts.

Policy recommendations must push for the formal adoption of the Avian-Optimized Agroforestry Protocol (AOAP) by regional agricultural extension services in Sumatra. This protocol provides farmers with a clear, science-based blueprint for management practices that maximize bird conservation benefits while simultaneously ensuring the provision of ecological services like pest control.

Implications exist for market mechanisms and consumer choice. The findings provide the necessary evidence to link premium pricing and ethical sourcing directly to quantifiable ecological performance. This creates a powerful economic incentive for Sumatran farmers to invest the time and labor required to maintain complex, high-diversity shade systems instead of converting to simplified monocultures.

The successful retention of forest-dependent species justifies the use of high-diversity shade coffee systems as compensatory mitigation sites (Molla et al., 2023). Government agencies and large corporations seeking to offset development impacts can utilize the AOAP to guide investments in agroforestry systems that are guaranteed to yield verifiable conservation outcomes, ensuring accountability in biodiversity offsetting.

The findings are fundamentally like that because high-diversity shade coffee systems function via structural mimicry (Millet et al., 2025). The multiple vertical layers (canopy, sub-canopy, coffee, understory) recreate the complex structural niches found in natural forests, providing distinct habitats for species that forage, nest, and take refuge at different heights, unlike the one-dimensional habitat offered by sun monocultures.

The significant decline in specialized guilds in S-SGC plots occurs because the simplification of the shade layer eliminates critical resource reliability. Specialized insectivores, for instance, rely on a constant, cool, humid micro-climate and stable leaf litter found under dense \text{CC} (68\%) to sustain their invertebrate prey base, resources that are instantly lost when \text{CC} drops to 35\% or lower.

The high predictive power of Shade Tree Basal Area (\text{BA}) is explained by the biological role of mature trees. Only large, old-growth native trees which drive high \text{BA} possess the necessary attributes (deep, furrowed bark, large structural branches, established epiphytes) to provide essential micro-habitats that small or non-native shade trees cannot offer, linking \text{BA} directly to habitat quality.

The ecological failure of sun monoculture (SM) is simply a consequence of unlivable micro-climatic conditions (Manson et al., 2024). High solar radiation and air temperature, combined with a lack of leaf litter, make the environment biologically uninhabitable for sensitive forest birds reliant on cool, shaded, moist refugia, forcing a functional collapse of the bird community down to a few heat-tolerant generalist species.

Future research must prioritize a comprehensive economic trade-off analysis that quantifies the yield stability and labor costs associated with maintaining the high Shade Tree Basal Area (\text{BA} 18.5 \text{ m}^2/\text{ha}) and high Canopy Closure (\text{CC} 68\%). This data is essential for convincing risk-averse farmers that the long-term ecological benefits translate into predictable and competitive economic returns.

Policy should focus on implementing financial incentive mechanisms that specifically reward farmers for maintaining or increasing the \text{BA} of native shade trees on their land (Bhat et al., 2023). This could include carbon sequestration payments, tax breaks, or access to premium certification markets, tying market value directly to the structural conservation metrics identified.

Long-term ecological monitoring is required to track the population dynamics of high-concern species, particularly Sumatran endemics, within the HD-SGC systems over a ten-year period (Figueroa-Alvarez et al., 2024). This longitudinal data will confirm if the systems function as long-term source habitats or merely as ecological sinks, validating the sustainable capacity of the AOAP.

Technological development should focus on creating a Farmer-Friendly Assessment Tool that utilizes simple remote sensing (e.g., drone imagery) or mobile applications to allow farmers to easily measure their plot's \text{BA} and \text{CC} against the AOAP's required thresholds. This ensures the protocol is easily adopted and implemented at the grassroots level.

CONCLUSION

The most critical finding is the quantitative identification of the specific structural determinants essential for avian conservation in the Sumatran Highlands. Multiple linear regression analysis confirmed that Shade Tree Basal Area (\text{BA}) and Canopy Closure (\text{CC}) are the most significant positive predictors of bird diversity (R^2=0.78, p < 0.001). This evidence is differentiated by the finding that High-Diversity Shade-Grown Coffee (HD-SGC) plots maintained a Functional Diversity Index (FDI 4.1) statistically equivalent to natural Forest Fragments (FDI 4.8), proving that complex structural mimicry is functionally viable. The results challenge the ecologically ambiguous "shade-grown" label by demonstrating that simplified systems register a steep 40\% drop in species richness, making them ineffective conservation tools.

The primary contribution of this research is the development and empirical foundation for the Avian-Optimized Agroforestry Protocol (AOAP), a prescriptive, science-based blueprint for sustainable management. This study significantly advances conservation metrics by shifting the analytical focus from mere species richness (SR) to functional diversity (FDI), providing a more robust measure of ecological health. By quantifying the exact structural requirements (high \text{BA} and \text{CC}), the research provides the necessary evidence to compel global coffee certification schemes to adopt precise, performance-based ecological standards, ensuring that market mechanisms deliver verifiable conservation outcomes in this critical biodiversity hotspot.

A key limitation of this ecological study is the absence of an integrated economic analysis, making it impossible to determine the yield stability and labor costs associated with maintaining the high \text{BA} and \text{CC} thresholds identified as ecologically optimal. Future research must, therefore, prioritize a comprehensive economic trade-off analysis that quantifies the long-term profitability of the AOAP for risk-averse farmers. Furthermore, long-term ecological monitoring over a ten-year period is required to track the population dynamics of high-concern Sumatran endemic bird species, confirming if the high-diversity shade systems function as sustainable source habitats rather than merely transient ecological sinks.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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