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Research Article

Analysis of Bird Vocal Bandwidth in Relation to Vegetation Structure Variability in Coffee Agroforestry Systems, Jember, Indonesia

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ABSTRACT

Bird vocalizations are crucial for communication and adaptation to environmental changes. As forests are converted to agriculture, agroforestry plays a key role in conserving biodiversity. This study examines vocal bandwidth variations in four bird species-Common Tailorbird (*Orthotomus sutorius*), Sooty-headed Bulbul (*Pycnonotus aurigaster*), Olive-backed Sunbird (*Cinnyris jugularis*), and Small Minivet (*Pericrocotus cinnamomeus*)-across three coffee agroforestry sites in Jember, Indonesia: Silo, Kluncing, and Kaliwining. The study explores how vegetation structure influences vocal adaptations using sound recordings, vegetation surveys, the Kruskal-Wallis test, and Pearson correlation analysis. Results show significant vocal bandwidth differences in Common Tailorbird and Sooty-headed Bulbul. Common Tailorbird exhibited the highest bandwidth variation in Silo (2.85 kHz), followed by Kluncing (2.30 kHz) and Kaliwining (1.10 kHz) ($p<0.001$). Similarly, Sooty-headed Bulbul showed significant variation, with the highest bandwidth in Silo (3.1 kHz), Kaliwining (3.5 kHz), and Kluncing (2.7 kHz) ($p<0.001$). However, bandwidth variation in Olive-backed Sunbird ($p = 0.12$) and Small Minivet ($p = 0.0014$) was not significant. Pearson correlation analysis indicated a strong but non-significant relationship between vegetation structure (Importance Value Index) and Sooty-headed Bulbul presence ($R^2 = 0.8999$, $p = 0.059$). These findings suggest that while vegetation influences some species, other factors like resource availability or human activity may also shape vocal adaptations. This study enhances understanding of bird communication in agroforestry, supporting biodiversity conservation and sustainable land management.

1. Introduction

Bird vocalizations are crucial in avian species ecological behavior and communication, playing a key role in territory defense, attracting mates, and social interactions between individuals (Zollinger 2015; Bradbury 2016). An important aspect of vocalization is bandwidth, which refers to the frequency range used by birds in their songs. Variations in vocal bandwidth can be influenced by various environmental factors, such as vegetation structure, human activities, and pressure from competitors or predators (Luther *et al*. 2016; Pandit *et al*. 2022). Vocal bandwidth, the range between the highest and lowest frequencies of bird calls, is a critical indicator of adaptation to habitat changes. Birds adjust their bandwidths

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to overcome environmental challenges like dense vegetation or anthropogenic noise to ensure effective communication. Studying bandwidth in agroforestry systems is particularly important because these landscapes combine ecological and agricultural elements, creating a heterogeneous environment (Job *et al*. 2016; Moura *et al*. 2016; Hao *et al.* 2024).

Agroforestry systems are ideal for studying vocalization variations because they combine natural forests and agricultural elements uniquely. This heterogeneous environment forces birds to adapt to fluctuating vegetation, microclimates, and human pressures. Unlike studies in urban or primary forests, this research focuses on vocalization dynamics in agroforestry using bandwidth analysis to reveal how birds navigate these complexities, contributing to biodiversity conservation efforts (Job *et al.* 2016). Vegetation structure plays a crucial role in shaping vocal bandwidth variation, with denser or more complex vegetation often leading to narrower bandwidths (Kammerichs-Berke *et al*. 2022).

The Jember coffee agroforestry system is one of the most dynamic and heterogeneous landscapes in East Java Province, Indonesia, where agricultural and forest plants interact (Dewi 2021; Firmansyah *et al*. 2023). The heterogeneity of agroforestry systems, characterized by a mosaic of dense and open vegetation interspersed with human activity, creates a dynamic acoustic environment. Birds in these landscapes must navigate challenges, such as variable vegetation density, which alters sound propagation, and human disturbances, which introduce competing noise. Coffee agroforestry is often a solution that balances biodiversity conservation and agricultural needs (Mukhlis *et al*. 2022). Birds play an important role as indicators of ecosystem health,. but they face specific challenges in these environments, such as variable vegetation, human disturbance, and fluctuating microclimates. These factors can alter how birds communicate, making studying their vocalizations essential for understanding the broader impacts of habitat modification on ecosystems. Unlike the dense, continuous canopies of primary forests and urban areas' fragmented and noisy settings, Jember's agroforestry systems present a patchwork of vegetation types. These range from densely shaded coffee plants to more open areas dominated by shaded trees, offering birds a mix of acoustic environments that demand flexible vocal adaptations.

Previous research has revealed that habitat changes, whether due to human activities or natural factors, can affect the vocal characteristics of birds, particularly their bandwidth (Luther *et al*. 2016; Friis *et al*. 2022). These studies showed that birds living in densely vegetated environments tend to have lower call frequencies and narrower bandwidths than those living in more open environments. This is because birds in dense vegetation must avoid sound distortions caused by echoes from dense plant structures. On the other hand, birds in open environments can use higher frequencies with wider bandwidths to maximize the communication distance (Job *et al*. 2016; Phillips *et al*. 2020; Chen *et al*. 2022). Most previous studies have focused on urban and primary forest habitats, leaving agroforestry systems that integrate agricultural and forest features. This study builds on the hypothesis that vegetation structure directly influences vocal bandwidth, testing whether the bandwidth of bird species in Jember's coffee agroforestry system follows similar patterns to those observed in more densely vegetated or open habitats.

By combining quantitative analyses of bird vocalizations with ecological variables, this study offers a fresh perspective on how habitat dynamics influence bird communication strategies. The urgency of this research lies in the increasing importance of agroforestry as a key strategy for biodiversity conservation amid the growing conversion of forest land into agricultural areas. Combining forest and agricultural elements, agroforestry creates a mosaic of diverse habitats, enabling various bird species to adapt to changing conditions. These adaptations are evident in birds' behavior and spatial distribution and how they communicate, particularly in their vocal characteristics. Understanding how bird species respond to habitat changes within agroforestry systems can provide valuable information for conservation efforts and sustainable land management. This study advances bird vocalization analysis by integrating Raven software for acoustic data processing and Python for high-resolution visualizations. The novel use of the Importance Value Index (IVI) links the vegetation structure to vocal adaptation, providing a unique ecological context. These innovative methods enhance our understanding of habitat-vocalization interactions in agroforestry systems and offer a replicable framework for similar ecosystems globally. The bird species selected for this study were chosen because of their high abundance in agroforestry systems, which ensured a sufficient dataset for accurate analysis. These species are considered representative of the broader bird community in the region because their vocal characteristics and adaptations reflect the ecological dynamics of agroforestry environments, which can be applied to species with lower abundance. By analyzing vocal bandwidth variation in four bird species across three agroforestry locations, this study contributes significantly to understanding how birds adjust their vocal characteristics in environments affected by human activities, such as agriculture. This study aimed to analyze the variation in bird vocal bandwidths across different agroforestry areas and determine the potential interaction between vegetation conditions and bandwidth changes. Given the general similarities between agroforestry systems, especially in tropical regions, the findings from this research can apply to agroforestry systems beyond Jember, providing broader insights into bird adaptation in these environments. This study is expected to open new avenues for further research to explore the relationship between habitat dynamics and vocal adaptation in bird species across various ecosystem types. The findings from this research are also relevant to supporting conservation policies and sustainable land management in Indonesia and other tropical regions, where agroforestry systems play an increasingly important role in biodiversity conservation.

2. Materials and Methods

This study was conducted at three locations in East Java Province, Indonesia, each representing different coffee agroforestry systems. It was conducted from May to August 2024 during the dry season because it generally provides better acoustic conditions for studying bird vocalizations, with less background noise, more consistent weather conditions, and clearer visibility, making capturing accurate data on vocalizations and habitat interactions easier. The research began with a pre-study activity to determine the locations and observation points, followed by observations and data collection, and concluded with a data analysis (Figure 1).

Each location reflects a unique agroforestry environment, with variations in vegetation structure and levels of human activity. Silo (-8.273724, 113.843191) is characterized by dense vegetation, predominantly coffee and silk trees (*Albizia chinensis*), with minimal human disturbance, offering a more homogeneous environment. Kluncing (7.968022, 114.044032) has a more open area and a varied habitat featuring multiple vegetation layers with minimal human disturbance, creating a rich and diverse environment. Kaliwining (-8.261130, 113.606372) presents intermediate conditions in terms of vegetation density and human disturbance (Figure 2). These locations were selected to explore how different habitat conditions influenced the vocal characteristics of the bird species analyzed. The vegetation composition

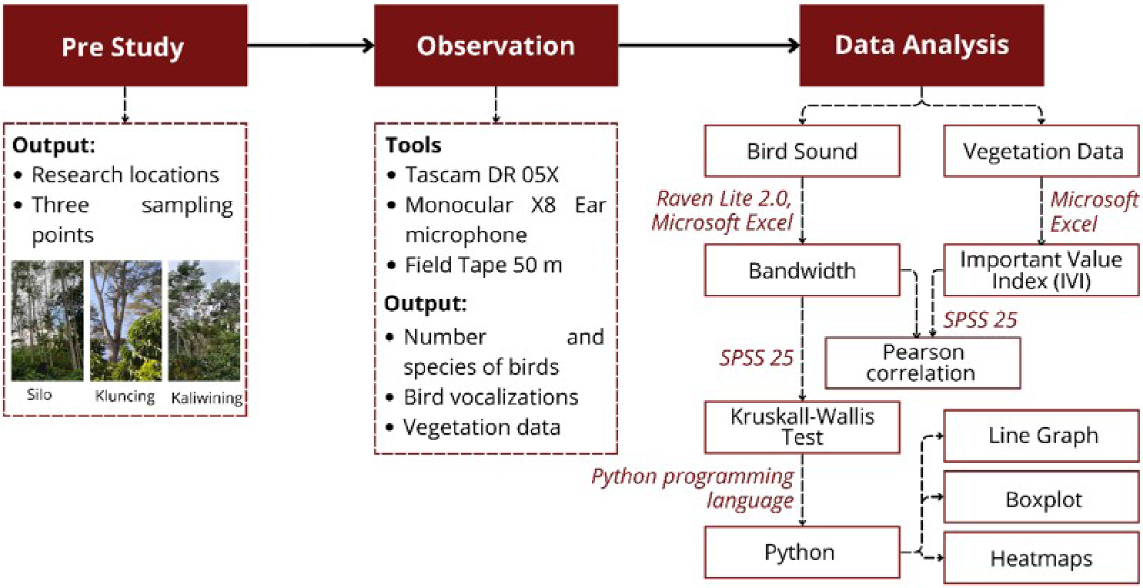

Figure 1. Workflow of the research process

Figure 2. (A) Map depicting the study locations in Indonesia, (B) highlighting the regencies of Jember (Yellow) and Bondowoso (Orange)

varied significantly across these locations, as indicated by the vegetation data collected during the observations, with statistical differences in the density and diversity of plant species.

Bird vocalizations, specifically calls, were recorded using a Tascam DR 05X and Monocular X8 Ear microphone. The Tascam DR 05X, with its high sensitivity and wide frequency range (20 Hz to 20 kHz), captures faint bird calls even in dense vegetation, whereas the directional design of the Monocular X8 Ear microphone minimizes ambient noise. Together, they ensure precise and clear recordings within a 20-meter radius, ideal for heterogeneous agroforestry environments. The recordings were conducted during peak bird activity hours (06-10 AM and 3-4 PM) to maximize the capture of vocalization behavior. Each recording session lasted approximately 20 minutes at each location and was repeated thrice to ensure data consistency. According to Bonthoux (2012), observations were made from a fixed point with a 20-meter observation radius, ensuring that vocalizations within this radius were recorded. Human activity characteristics and other vocal disturbances were noted during each observation session. To analyze shade tree vegetation, a 20 × 20 m transect method was employed (Alder and Synnott 1992). This method involves recording the type and number of plants, specifically focusing on canopy-level vegetation, at each bird vocalization observation point. Transects were placed at the respective bird observation locations to ensure spatial alignment with the focal study areas.

The recorded vocalizations were then processed and analyzed using Raven Lite 2.0 software to extract each vocalization's bandwidth (the difference between the highest and lowest frequencies). Recordings were conducted during peak bird activity hours to ensure data quality and to minimize background noise. A directional Monocular X8 Ear microphone was used to isolate the target calls-recordings with excessive noise or low signal-to-noise ratio (<15 dB) were excluded. Raven Lite 2.0 software was used for analysis, set at a 44.1 kHz sampling rate with a 1-10 kHz band-pass filter. Additionally, the number of notes in each vocalization was counted, and the relationship between the number of notes and bandwidth was analyzed for each species. Bandwidth and note count were selected as metrics of interest because they can reveal how birds adapt their vocalizations to environmental conditions, such as vegetation density and human disturbance, thereby providing insights into their communication strategies in agroforestry systems.

For data analysis, normality testing was performed using the Shapiro-Wilk test. The variables tested for normality included vocal bandwidth and note count to determine whether their distributions met the assumptions for the parametric analysis. For species with non-normally distributed bandwidth data, the Kruskal-Wallis test was used to assess the differences in vocalization bandwidth across the three locations. Statistical significance was set at $P < 0.05$. Additionally, Pearson correlation analysis explored the relationship between vegetation structure (measured using the Important Value Index, or IVI) and average bird bandwidth for each species. The IVI was calculated based on vegetation species' density, dominance, and frequency at each location.

IVI = Relative Density + Relative Frequency + Relative Dominance (vegetation only)

Where: Relative Density = (Number of individuals of a species / Total number of individuals of all species) × 100; Relative Frequency = (Frequency of a species / Total frequency of all species) × 100; Relative Dominance (vegetation only) = (Basal area of a species / Total basal area of all species) × 100

IVI values were calculated separately for each observation point to capture the local vegetation structure and averaged across transects to derive site-specific values for analysis. Dominant species, such as *Coffea canephora* and *Falcataria moluccana*, identified through IVI rankings, were analyzed for their potential influence on bandwidth variation owing to their contributions to vegetation density and canopy structure. As a comprehensive measure integrating density, frequency, and dominance, the IVI effectively links vegetation structure to bird vocal adaptations, highlighting key habitat features such as dense vegetation that may act as acoustic barriers.

The data analysis for this study was performed using Python. The visualizations produced, including line graphs, boxplots, and heatmaps, were created to illustrate the variation in bird vocal bandwidth across the three observation locations: Silo, Kluncing, and Kaliwining. Heatmaps were constructed explicitly for all species, aiding in interpreting how environmental factors like vegetation density and human disturbance influence vocalization patterns.

Several Python libraries were utilized in creating these visualizations, including Matplotlib version 3.3.4 and Seaborn version 0.11.1. Matplotlib generated graphics such as boxplots and line plots that display bandwidth variation with accompanying error bars. On the other hand, Seaborn was used to facilitate the creation of heat maps that depicted the average bandwidth differences among bird species at various locations.

3. Results

Based on the analyzed data, 20 bird species were assessed, with 701 frequency notes collected. The 701 frequency notes were distributed proportionally across species and locations based on their relative abundance and activity during observations, ensuring balanced data representation. Bandwidth data for four bird species, Common Tailorbird, Sooty-headed Bulbul, Olive-backed Sunbird, and Scarlet Minivet, showed average variation across the frequency notes analyzed. These species were selected because of their abundance in the agroforestry system, ensuring a reliable dataset and ecological relevance in the region. The results of the normality test analysis indicated that the bandwidth population for the four species did not follow a normal distribution; thus, the Kruskal-Wallis non-parametric test was used to assess differences. Given the non-parametric nature of the data, the Kruskal-Wallis test was used to compare the bandwidth variations across locations. Other non-parametric tests, such as the Mann-Whitney U test, were considered for pairwise comparisons but were not applied to avoid issues with multiple testing. The excluded species were omitted from the analysis because of insufficient data for a robust statistical evaluation.

Based on the results of the Kruskal-Wallis test conducted on the four bird species (Table 1), it was found that the two species showed statistically significant distribution differences across various locations. The Common Tailorbird had the highest statistical value, at 51.44, with a very small p-value (6.75 x 10^{-12}), indicating significant distribution differences among the observation sites (Figure 3). The Sooty-headed Bulbul also showed significant differences, with a statistical value of 24.76 and a p-value of 4.19 x 10^{-6}, confirming significant variation in its distribution. However, the other two species yielded different results. The Olive-backed Sunbird had a statistical value of 4.26 with a p-value of 0.12, indicating that the distribution differences across locations were not statistically significant. Conversely, the Scarlet Minivet showed significant distribution differences, with a statistical value of 13.12 and a p-value of 0.0014, indicating a different distribution pattern in some observation sites.

Bandwidth variation was observed in the Olive-backed Sunbird, with averages of 2.9 kHz in Silo, 3.2 kHz in Kluncing, and 2.6 kHz in Kaliwining, though these differences were not statistically significant (Figure 4). In contrast, the Common Tailorbird showed significant variation across locations, with bandwidth

Table 1. Kruskal-wallis test results for bird species vocalization bandwidth across study locations

Birds species	Kruskal-Wallis statistic	p-value
Common Tailorbird *Orthotomus sutorius*	51.43	6.74^{-12*}
Sooty-headed Bulbul *Pycnonotus aurigaster*	24.75	4.18^{-6*}
Olive-backed Sunbird *Cinnyris jugularis*	4.25	0.12
Small Minivet *Pericrocotus cinnamomeus*	13.11	0.002^{*}

*: significant result

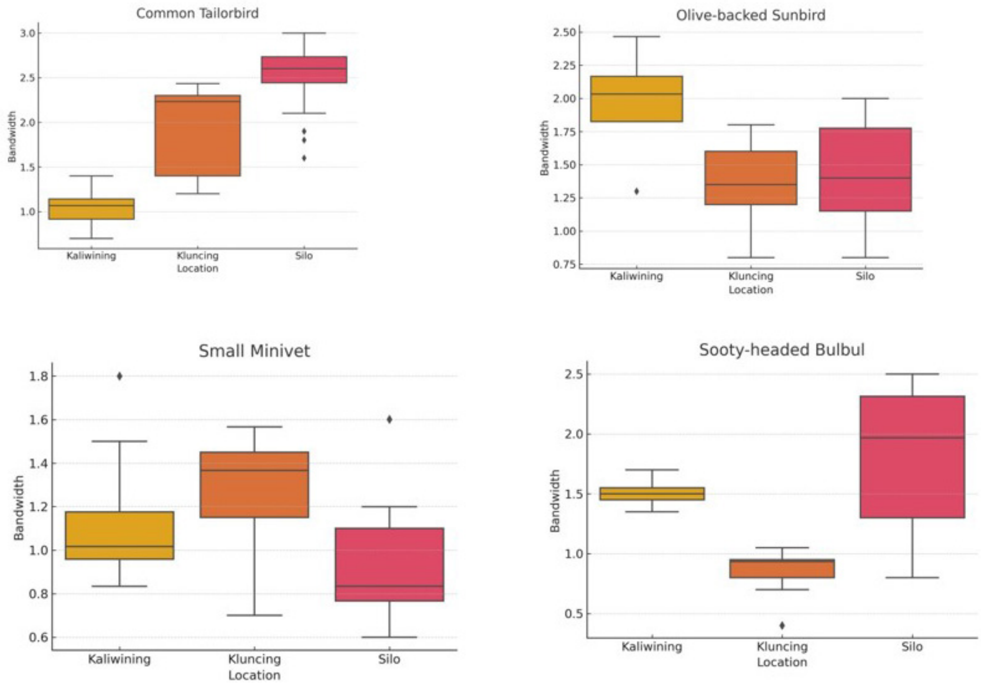

Figure 3. Boxplot showing the differences in average bandwidth across study locations

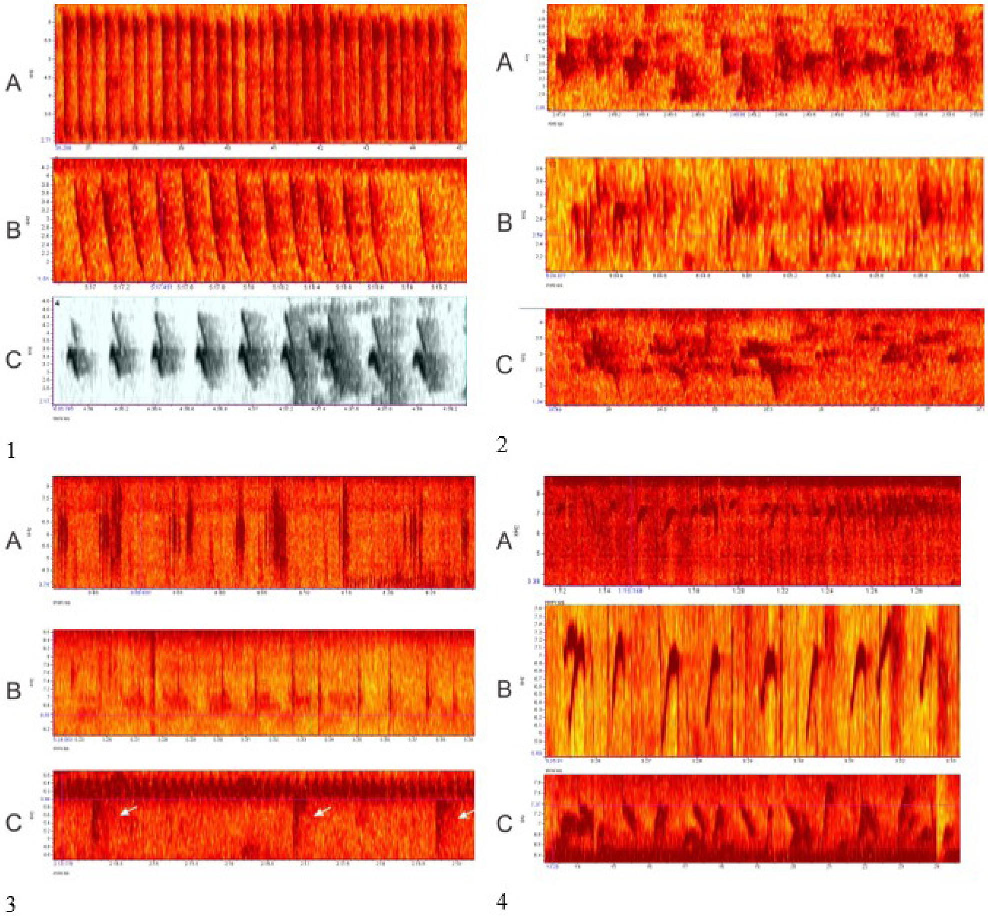

Figure 4. Compilation of sonograms for four bird species. 1: Common tailorbird, 2: Sooty-headed bulbul, 3: Olive-backed Sunbird; 4: Small minivet; A: Silo, B: Kluncing, C: Kaliwining. White arrows indicate vocal signals amid natural noise

averages of 2.3 kHz in Silo, 3.4 kHz in Kluncing, and 2.8 kHz in Kaliwining.

Figure 5 shows the bandwidth variation of four bird species-Common Tailorbird, Olive-backed Sunbird, Small Minivet, and Sooty-headed Bulbul-relative to the number of notes in their songs, highlighting distinct vocalization patterns. The Sooty-headed Bulbul exhibited significant differences across locations, with average bandwidths of 3.1 kHz in Silo, 2.7 kHz in Kluncing, and 3.5 kHz in Kaliwining. The Common Tailorbird showed notable variation, with frequencies ranging from 1 to 2.5 kHz and a sharp bandwidth increase between the 10th and 35th notes, indicating high vocal complexity.

The Olive-backed Sunbird exhibited a narrower, stable bandwidth (1-1.5 kHz) with minor fluctuations, indicating simpler frequency variation than the Common Tailorbird. The Small Minivet showed consistent bandwidth stability (1-1.2 kHz), while the Sooty-headed Bulbul had the narrowest and most homogeneous bandwidth (0.9-1.1 kHz) with minimal variation.

The results showed significant variation in the strength and direction of the relationship between vegetation's Importance Value Index (IVI) and the average bird value for the four bird species analyzed (Table 2). IVI describes the importance of a species in an ecosystem based on its dominance, density, and frequency of occurrence. However, there was no substantial evidence of the influence of shade tree vegetation on bandwidth variation in the present study (Table 3). The analysis revealed that Sooty-headed Bulbul had a strong but statistically insignificant relationship with vegetation IVI (Table 3). This is indicated by a coefficient of determination (R^2) of 0.89999, suggesting that 89.99% of the variation in the average value of Sooty-headed Bulbul could be explained by the vegetation IVI. A regression coefficient of 0.53 indicates a positive relationship, meaning that the higher the IVI of a vegetation species, the higher the average presence of Sooty-headed Bulbul in that location. However, a p-value of 0.059 indicates that this relationship is not statistically significant, although it is close to the significance threshold (0.05). In contrast, the Common Tailorbird showed a very weak relationship with the IVI. The very low R^2 of 0.0878 indicates that only 8.78% of the variation in the presence of the Common Tailorbird can be explained by the vegetation IVI. A regression coefficient of 0.0106 suggests an almost neutral relationship between the two variables, and a p-value of 0.8084 indicates that the result is not statistically significant. This weak relationship suggests that the presence of a Common Tailorbird may be influenced more by factors other than vegetation structure, such as the availability of insects or other environmental factors not considered in this analysis.

The Olive-backed Sunbird showed a weak relationship with vegetation IVI, with an R^2 of 0.2406, meaning that only about 24.06% of the variation in

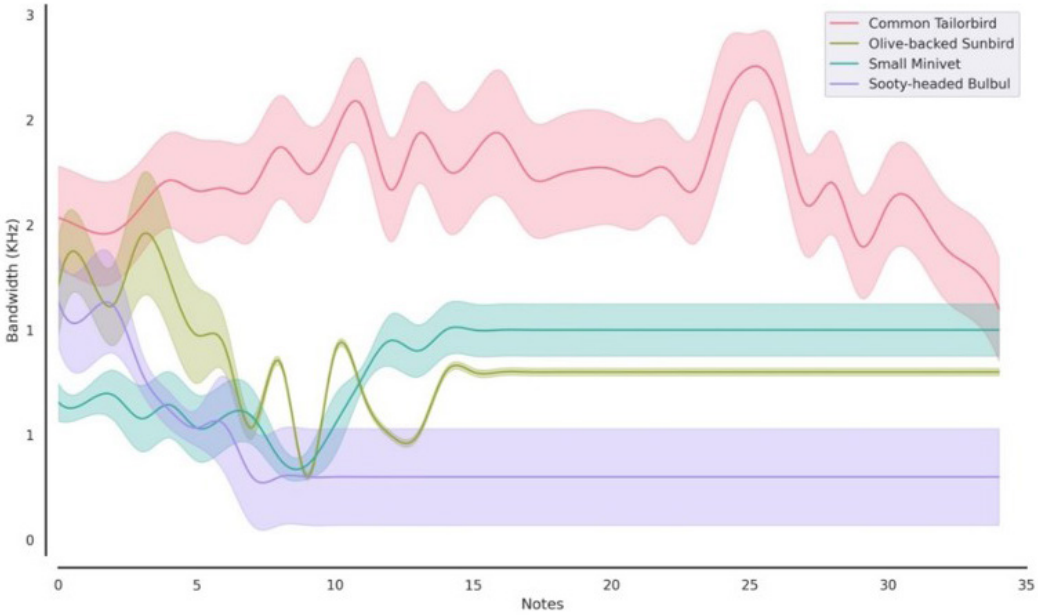

Figure 5. Bandwidth variation (kHz) of four bird species across vocalization notes

Table 2. Important value index (IVI) of plants according to location. RA: Relative Abundance, RF: Relative Frequency

Location	Plant species	RA	RF	IVI	Location	Plant species	RA	RF	IVI
Silo	*Coffea canephora*	53.62	33.32	104.26	Kluncing	*Parkia speciosa*	0.15	1.67	2.36
	Falcataria moluccana	39.93	33.32	143.03		*Hibiscus tiliaceus*	0.30	3.33	5.25
	Swietenia macrophylla	3.073	11.10	22.94		*Dimocarpus longan*	0.15	1.67	1.87
	Annona muricata	2.78	11.10	14.33		*Euphorbia pulcherrima*	0.74	1.67	2.83
	Cocos nucifera	0.56	11.10	15.41		*Gliricidia sepium*	10.70	11.67	32.52
Kaliwining	*Leucaena leucocephala*	39.81	21.74	61.53		*Melia azedarach*	0.59	6.67	14.38
	Samanea saman	12.61	21.74	34.35		*Persea americana*	1.04	5.00	6.61
	Swietenia macrophylla	0.96	8.70	9.67		*Swietenia macrophylla*	0.15	1.67	2.58
	Falcataria moluccana	5.83	17.38	23.20		*Durio zibethinus*	0.15	1.67	2.05
	Durio zibethinus	0.96	8.68	9.67		*Syzygium spp.*	0.15	1.67	2.11
	Coffea canephora	39.84	21.74	61.53		*Annona muricata*	0.15	1.67	2.11
Kluncing	*Coffea canephora*	75.04	23.33	116.07		*Cajanus cajan*	0.15	1.67	1.85
	Falcataria moluccana	5.65	16.67	40.84		*Enterolobium cyclocarpum*	1.04	6.67	45.10
	Calliandra calothyrsus	3.57	10.00	16.67					

Table 3. Summary of pearson correlation results

Bird species	R^2	Regression coeffficient	Intercept	P-value
Common Tailorbird *Orthotomus sutorius*	0.087832	0.010645	1.58398	1.58398
Sooty-headed Bulbul *Pycnonotus aurigaster*	0.899913	0.529956	0.480704	0.480704
Olive-backed Sunbird *Cinnyris jugularis*	0.24061	0.019273	0.987015	0.987015
Small Minivet *Pericrocotus cinnamomeus*	0.925632	-0.01359	1.547205	1.547205

the presence of the Olive-backed Sunbird could be explained by IVI. A regression coefficient of 0.0193 indicates an almost neutral relationship and a p-value of 0.6736 suggests this relationship is insignificant. Similar to the Common Tailorbird, this result suggests that vegetation structure may not be the main factor influencing the presence of olive-backed sunbirds. Further research is needed to identify other potentially relevant factors, such as food resources or competition dynamics between species.

The Small Minivet also showed a strong but negative relationship with the IVI. An R^2 of 0.9256 indicated that vegetation IVI could explain 92.56% of the variation in the presence of the Scarlet Minivet. However, a regression coefficient of -0.0136 suggests that this relationship is negative, meaning that the higher the vegetation IVI, the lower the Scarlet Minivet's presence in that location. Nonetheless, a p-value of 0.1758 indicated this relationship was not statistically significant. This intense negative relationship might reflect the preference of Scarlet Minivet for areas with sparser vegetation or more open vegetation structures, although the existing data are insufficient to support a firm conclusion.

The generated heatmap illustrates the distribution of average bandwidth values for the four bird species across three different locations: Silo, Kluncing, and Kaliwining (Figure 6). Each species exhibited a unique distribution pattern, reflecting how specific environmental factors at each location might influence the development of bird bandwidth. The Sooty-headed Bulbul showed relatively high and consistent average bandwidth values across all the locations. The highest value was found in Silo (average = 2.23), followed by Kaliwining (average = 1.60), whereas in Kluncing, the bandwidth value was slightly lower (average = 0.93).

The Common Tailorbird exhibited more significant variation in the distribution of the average bandwidth values across the three locations. The highest value was recorded in Silo at 2.85, while in Kluncing, it was 2.30, and in Kaliwining, it was much lower, at only 1.10. This striking difference suggests that Silo may offer environmental conditions that are more conducive to the development of species bandwidth. Silo likely has denser vegetation yet is aligned with the ecological needs of the Common Tailorbird for communication, such as more open trees or shrubs. However, the less favorable conditions in Kaliwining

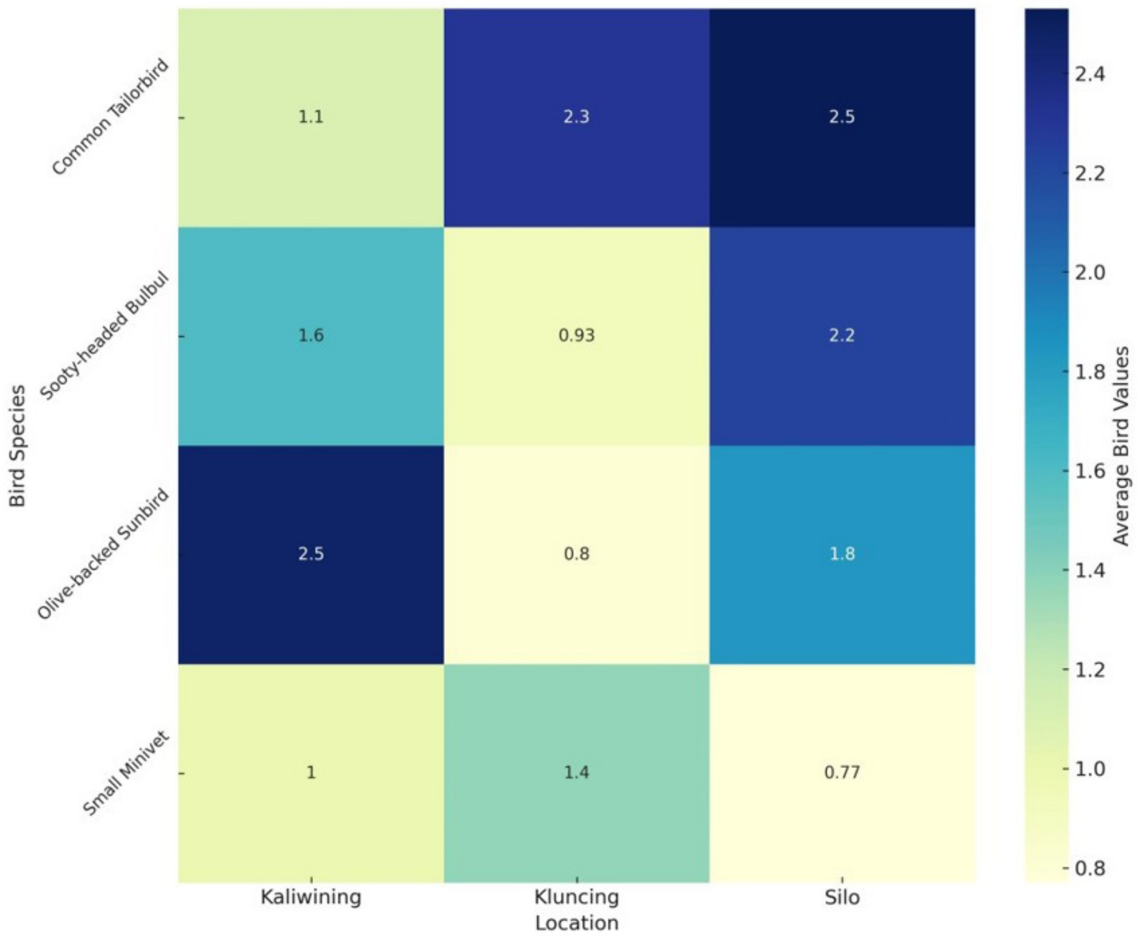

Figure 6. Heatmap comparing the average birdsong bandwidth across three locations

may limit this species' bandwidth development. The Olive-backed Sunbird displayed a varied bandwidth pattern across each location, with the highest value in Silo at 1.83, followed by Kaliwining at 2.47, and significantly dropping in Kluncing to only 0.80. This species is a nectarivorous bird, heavily reliant on the availability of flowers as its primary food source.

4. Discussion

The differences in bandwidth indicate variations in the vocal characteristics of the Common Tailorbird, which may be caused by factors such as habitat variation, geographic conditions, or differences in environmental pressures such as noise levels or dominant vegetation structures in each location (Francis 2015). The primary driver of the bandwidth variation appears to be the vegetation density at each location. Silo, for example, may have a more enclosed habitat or denser vegetation conditions, with homogeneous sengon shade trees planted at approximately 3×3 m spacing and canopy diameters reaching 5 m, creating a dense environment for bird activity, causing birds in that area to produce calls with narrower bandwidths to reduce interference from sound reflections or dense vegetation (Phillips *et al*. 2020b). In contrast, Kluncing, which has a more open area and different environmental conditions, may allow birds to use wider bandwidths for long-distance communication or in reproductive contexts (Job *et al*. 2016). (Nemeth *et al*. 2013) found that birds in densely vegetated forests often use lower frequencies and narrower bandwidths to mitigate the sound distortion caused by echoes and reflections. Other factors, such as predation pressure, social interactions among individual birds, or even adaptation to human noise levels at these locations, may also influence these vocal variations (Job *et al*. 2016; Phillips *et al*. 2020a).

In Silo, narrower bandwidths in the Common Tailorbird (2.85 kHz 2.85kHz) correlate with denser vegetation characterized by a higher Importance Value Index (IVI) for shade trees like *Albizia chinensis* (IVI = 143.03). The dense canopy structure in Silo likely increases sound attenuation and reverberation, compelling birds to reduce their bandwidth to minimize signal distortion. Additionally, the lower ambient noise levels in Silo may further support this adaptation, as less competition with external noise enables more precise frequency use.

The varying habitat conditions at each location may influence the vocal adaptation of the Sooty-headed Bulbul, where birds in Kaliwining have a broader bandwidth than those in Silo and Kluncing. A larger bandwidth may provide an advantage to Sooty-headed Bulbul for communication in more open areas or with high environmental noise, while the narrower bandwidth in Kluncing and Silo may reflect more enclosed environmental conditions or denser vegetation (Mardiastuti *et al*. 2019, 2020). Sooty-headed Bulbul is an urban bird species often found in open areas with warmer environments and higher light intensity; birds can communicate more effectively using broader bandwidths (Saroyo *et al*. 2024). However, this broader communication range comes with trade-offs, including higher energy expenditure to sustain vocalization and an increased risk of predation due to the heightened detectability of calls.

These findings are important in the context of ecology and conservation, especially in agroforestry areas such as Silo, Kluncing, and Kaliwining. Agroforestry offers a heterogeneous environment that can create both challenges and opportunities for bird species regarding communication and adaptation. By studying these vocal variations, researchers can better understand how bird species such as the Sooty-headed Bulbul adapt to environmental changes caused by human activities such as agriculture or deforestation and how these factors affect the local ecosystem as a whole. The sooty-headed Bulbul is a cosmopolitan bird that can adapt to urban areas and forest edges, which may differ significantly from birds adapted to forested areas (Mardiastuti *et al*. 2020). This study emphasizes the need for diverse habitat structures in agroforestry systems to support bird vocal adaptation. Heterogeneous landscapes combining dense vegetation and open areas can benefit species such as the Common Tailorbird and Sooty-headed Bulbul, enhancing habitat suitability and biodiversity.

The Common Tailorbird experiences morphological changes in its bandwidth, where its vocal frequency is not monotonous but dynamically varied, especially from the middle to the end of its song. This sharp frequency change may reflect the important role of the song in communication, whether to attract mates, mark territories, or communicate with other social groups (To *et al*. 2021). This increase in bandwidth may also indicate specific adaptations to the surrounding environment, where the Common Tailorbird may need to modify its frequency to penetrate vegetation barriers or distinguish its song from other environmental sounds (Hao *et al*. 2024). Similarly, (Nemeth *et al*. 2012) showed that birds adjust their bandwidth between residential areas and urban forests, showcasing their environmental adaptation. Thus, this variation in bandwidth shows that the Common Tailorbird song functions not only as a communication tool but also as a response to environmental pressures or diverse ecological conditions (Phillips *et al*. 2020b). The dynamic bandwidth changes in the Common Tailorbird likely reflect environmental adaptation, with narrower bandwidths in dense vegetation enhancing communication clarity and broader ranges in open habitats facilitating long-distance signaling. Similar patterns observed in species such as the Yellow-vented Bulbul and Rufous-capped Warbler suggest that these adaptations may influence reproductive success and survival by improving mate attraction and territorial defense.

Overall, this graph illustrates that the Common Tailorbird has the most dynamic frequency variation in its song, while the Sooty-headed Bulbul has the most consistent and stable song. Once again, this demonstrates that the Sooty-headed Bulbul is part of a cosmopolitan bird group with low dependence on specific environmental conditions (Mardiastuti *et al*. 2020). The Olive-backed Sunbird and Small Minivet occupy positions between these two extremes, with the Olive-backed Sunbird showing slightly more variation than the Small Minivet.

The Pearson correlation analysis showed no firm evidence of differences between the vegetation and bandwidth. However, the sooty-headed bulk has a p-value that is quite close to significant. This suggests that, although there is a strong indication that the presence of Sooty-headed Bulbul is influenced by vegetation structure, this finding requires further analysis or additional data to reach a more conclusive result. This consistency suggests that this species has broad tolerance to various environmental conditions and can adapt well to locations with varying vegetation characteristics and habitat conditions. Other species dependent on densely vegetated habitats must adjust their frequencies accordingly (Kight and Swaddle

2015; Mena and Garcia 2018). Sooty-headed Bulbul is a generalist species that can thrive in various habitats, from agricultural areas to secondary forests (Mardiastuti *et al*. 2019, 2020). However, the decline in bandwidth in Kluncing is assumed to be due to factors such as changes in vegetation structure compared with the other two locations. This indicates that although this species can survive under various conditions, there are certain limits to its ability to maintain bandwidth variation when environmental factors change significantly (Nemeth *et al*. 2012). Kluncing may not provide enough suitable flowering vegetation, affecting the ability of nectarivorous species to explore habitats, leading to narrower bandwidths, as they may not need to communicate over long distances or in large areas with less food availability (Davis *et al*. 2015). This highlights the importance of flowering vegetation as a key determinant of this species's distribution and bandwidth variation.

The Small Minivet exhibited more dynamic fluctuations in the average bandwidth values across the three locations. In Kaliwining, the bandwidth was recorded at 1.00, then slightly increased in Kluncing to 1.37, and dropped again in Silo to its lowest value of 0.77. This species is usually found in areas with more open vegetation or higher tree canopies, around 20 meters in height, so that these fluctuating bandwidth changes may indicate a preference for more specific habitats. The increase in bandwidth in Kluncing suggests that this location supports the ecological need of the Small Minivet to adapt to more open vegetation. However, the lower value for Silo suggests that the habitat at this location may not provide ideal conditions for this species, especially if the vegetation structure is more closed or lower (LaZerte *et al*. 2015; Phillips Chooper *et al*. 2020). This could affect the birds' ability to transmit communication signals effectively. The expansion of bandwidth in open habitats likely reflects the adaptation of birds, allowing their signals to travel further and more efficiently across expansive areas, facilitating better communication over long distances.

The heatmap comparison results show that each bird species has different habitat preferences that can affect bandwidth development at each location. Silo appears to support bandwidth development for the Common Tailorbird and Olive-backed Sunbird, whereas Kluncing supports Small Minivet. Although Kaliwining provides relatively good bandwidth values for most species, it may have limitations in providing optimal conditions for certain species. Building agroforestry with heterogeneous vegetation is essential, as it offers dense environments with higher humidity and shaded areas for species that need cooler temperatures and open vegetation for species that thrive at higher temperatures and light intensity. With this understanding, further research can explore the interactions between bird species and their habitats in more depth to conserve bird populations in diverse ecosystems.

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