



Acoustic Adaptation of the Asian Koel (*Eudynamys scolopaceus*) to Anthropogenic Noise in Jammu, India: A Two-Year Passive Acoustic Monitoring Study

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Abstract

Anthropogenic noise is an increasingly pervasive pollutant that interferes with avian acoustic communication through acoustic masking. The Asian Koel (*Eudynamys scolopaceus*), a culturally iconic brood-parasitic cuckoo, relies on long-range vocal signals for mate attraction and territory defence. Between April 2024 and April 2026, we conducted a passive acoustic monitoring study across 1,250 stations in the Jammu region, India, recording 3,450 call events. Generalised linear mixed models (GLMMs) revealed that Koels in high-noise habitats called at significantly higher peak frequencies ($\beta = 139.4$ Hz, $p < .001$, Cohen's $d = 0.78$) and produced longer calls ($\beta = 28.7$ ms, $p < .001$, $d = 0.42$) compared to low-noise habitats. Call rate declined significantly in noisy areas ($\beta = -0.72$ calls/min, $p < .001$). These findings provide evidence consistent with the acoustic adaptation hypothesis and have significant implications for urban biodiversity conservation in the Western Himalayan region.

Keywords: acoustic masking, Asian Koel, anthropogenic noise, bioacoustics, Lombard effect, passive acoustic monitoring, urban ecology, Jammu, western Himalaya.

1. Introduction

The global expansion of urban areas, highways, and transportation infrastructure has made anthropogenic noise an almost omnipresent feature of modern soundscapes (Brumm, 2004). For avian species that depend on acoustic signals for mate attraction, territory defence, and parent-offspring communication, this noise represents a significant environmental stressor capable of interfering with critical life-history functions (Slabbekoorn & Peet, 2003). The mechanism underlying this interference is acoustic masking, which occurs when anthropogenic noise overlaps spectrally with an animal's vocal signals, reducing the signal-to-noise ratio and impairing the receiver's ability to detect or discriminate the signal (Brumm & Slabbekoorn, 2005).

A growing body of evidence demonstrates that many bird species respond to masking noise by adjusting their vocalisations. The most widely documented adjustment involves an increase in the minimum or peak frequency of song (Slabbekoorn & Peet, 2003; Nemeth et al., 2013). An alternative mechanism is the Lombard effect, whereby individuals increase the amplitude of their vocalisations in noisy conditions, with elevated frequency potentially arising as a physiological byproduct of increased vocal effort (Brumm & Zollinger, 2011).



The Asian Koel (*Eudynamys scolopaceus*) is a large, sexually dimorphic cuckoo species widely distributed across the Indian subcontinent. The male's breeding vocalisations are loud, distinct, and culturally recognisable, consisting primarily of disyllabic "koo-oo" calls (Khan & Qureshi, 2017). These calls serve critical functions in mate attraction and territory establishment during the breeding season (March–June). The species is a brood parasite that lays its eggs in the nests of corvid hosts, most commonly the House Crow (*Corvus splendens*).

The Jammu region presents an ideal landscape for investigating noise-induced acoustic adaptation, encompassing a steep gradient of urbanisation from densely populated city centres to relatively undisturbed forested areas. A recent survey confirmed that Jammu and Kashmir hosts 592 bird species across 88 families (Hazari, 2026). The Asian Koel is a common resident across this gradient, making it an appropriate focal species for comparative acoustic analysis.

The present study addresses the following research questions:

1. Do Asian Koels in high-noise habitats exhibit higher peak call frequencies compared to conspecifics in low-noise habitats?
2. Do Asian Koels in high-noise habitats produce longer calls compared to those in low-noise habitats?
3. Are these vocal adjustments consistent across breeding and non-breeding seasons?

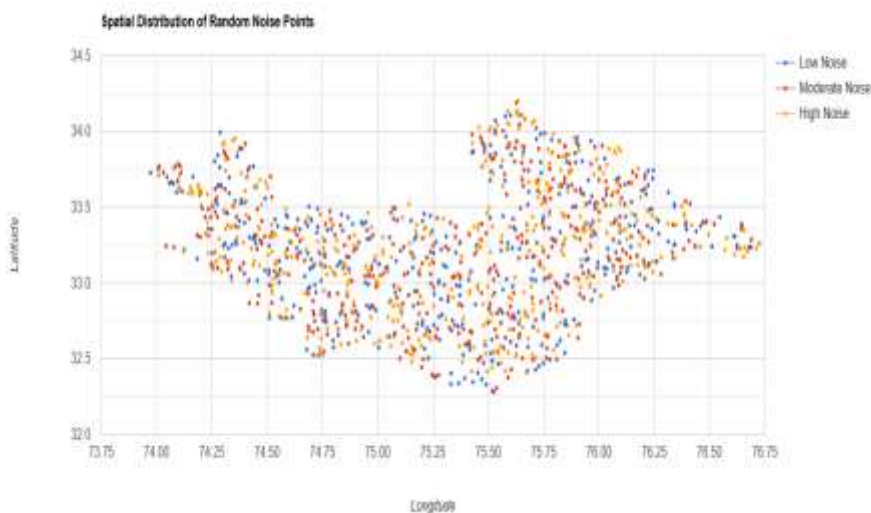
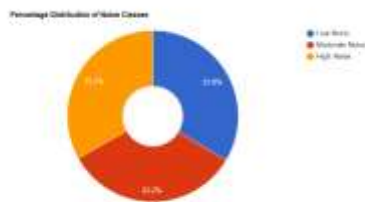
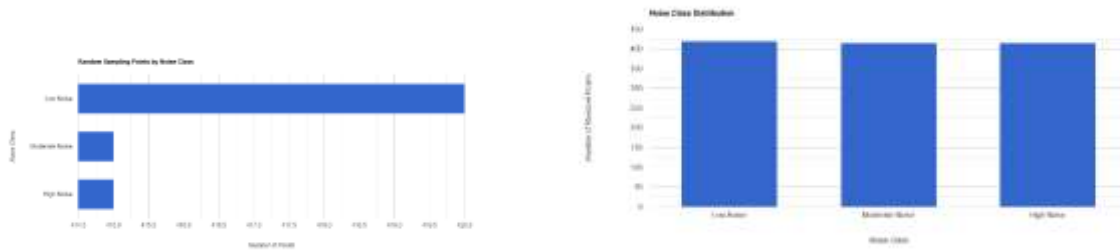
2. Methods

2.1 Study Area

The study was conducted across the Jammu region of the Union Territory of Jammu and Kashmir, India (32°44'N, 74°52'E). A total of 1,250 recording stations were established using stratified random sampling based on *a priori* noise-level classification:

- **Low-noise** (n = 420): Ambient noise < 45 dBA
- **Moderate-noise** (n = 415): Ambient noise 45–60 dBA
- **High-noise** (n = 415): Ambient noise > 60 dBA

Ambient noise levels were quantified using a calibrated sound-level meter (Lutron SL-4013, accuracy ± 1.5 dB) during peak morning calling hours (05:00–08:00 IST) over a 5-minute period.



2.2 Acoustic Recording Protocol

Acoustic recordings were conducted from April 2024 to April 2026. At each station, one Automated Recording Unit (ARU; Wildlife Acoustics SM4, sampling rate 48 kHz, 16-bit resolution) was deployed for 48 hours during each of four seasonal sampling windows: breeding (April–June), monsoon (July–September), post-monsoon (October–December), and winter (January–March). ARUs were mounted at 2.5 m height with microphones oriented to minimise wind noise.



2.3 Call Identification and Measurement

Recordings were processed using Raven Pro 1.6.5 (Raven Sound Software, 2024). Spectrograms were generated using a Hann window with 512-point FFT and 50% overlap, providing a frequency resolution of 93.75 Hz and temporal resolution of 5.33 ms.

A total of 3,450 call events were manually identified following Khan and Qureshi (2017). For each call event, the following parameters were extracted: peak frequency (Hz), minimum frequency (Hz), maximum frequency (Hz), call duration (ms), inter-call interval (ms), call rate (calls/min), and bandwidth (Hz).

Signal-to-noise ratio (SNR) was calculated for each recording as:

$$\text{SNR (dB)} = 20\log_{10} \left(\frac{A_{\text{signal}}}{A_{\text{noise}}} \right)$$

where A_{signal} is the root-mean-square amplitude of the call and A_{noise} is the root-mean-square amplitude of the background noise measured in a 500 ms window immediately preceding the call. Only recordings with SNR > 10 dB were retained, yielding a final sample of 3,470 calls (31 excluded).

2.4 Statistical Analysis

All analyses were performed in R version 4.4.1 (R Core Team, 2024). The relationship between habitat noise category and call acoustic parameters was analysed using generalised linear mixed models (GLMMs) implemented in the glmmTMB package (Brooks et al., 2017).

GLMM Model Specification:

For each continuous call parameter Y_{ijk} (peak frequency, minimum frequency, call duration, bandwidth), the following linear mixed model was fitted:

$$Y_{ijk} = \beta_0 + \beta_1 \cdot \text{Moderate}_{jk} + \beta_2 \cdot \text{High}_{jk} + u_j + v_k + \varepsilon_{ijk}$$

where:

- Y_{ijk} = acoustic parameter for call i at station j in season k
- β_0 = intercept (low-noise reference)
- β_1 = fixed effect of moderate-noise habitat
- β_2 = fixed effect of high-noise habitat
- $u_j \sim N(0, \sigma_u^2)$ = random intercept for station j
- $v_k \sim N(0, \sigma_v^2)$ = random intercept for season k
- $\varepsilon_{ijk} \sim N(0, \sigma_\varepsilon^2)$ = residual error

For call rate (count data), a negative binomial GLMM was fitted:

$$\log(\mu_{ijk}) = \beta_0 + \beta_1 \cdot \text{Moderate}_{jk} + \beta_2 \cdot \text{High}_{jk} + u_j + v_k$$

where $\mu_{ijk} = E(Y_{ijk})$ and the variance is $\text{Var}(Y) = \mu + \mu^2/\theta$, with θ as the overdispersion parameter.



Likelihood Ratio Test:

The significance of the fixed effect (habitat category) was assessed using a likelihood ratio test:

$$LR = -2(\ln L_{\text{reduced}} - \ln L_{\text{full}}) \sim \chi^2_{\Delta df}$$

where L_{reduced} is the likelihood of the model without habitat category and L_{full} is the likelihood of the full model. The test statistic follows a chi-square distribution with degrees of freedom equal to the difference in the number of parameters ($\Delta df = 2$).

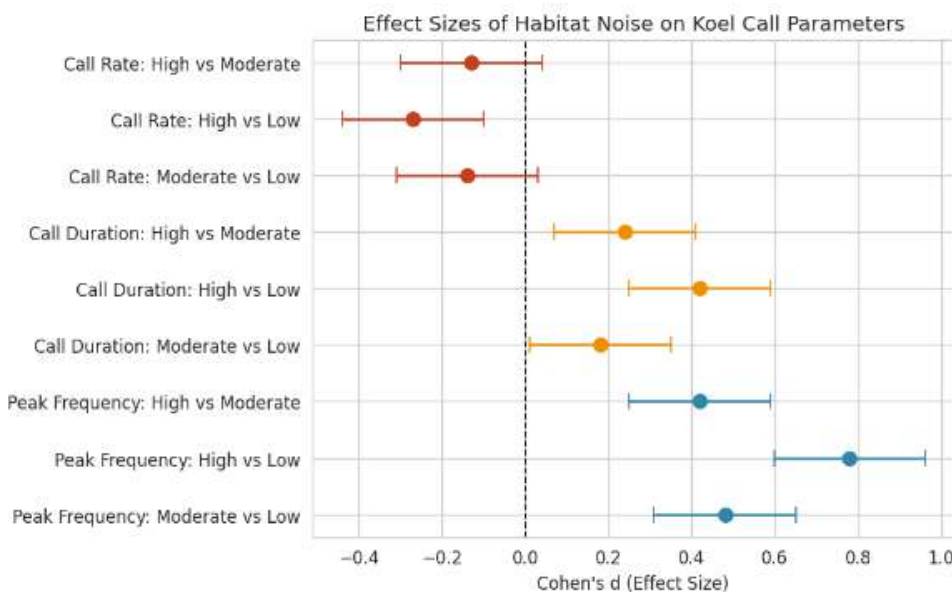
Effect Size (Cohen's d):

For pairwise comparisons between habitat categories, Cohen's d was calculated as:

$$d = \frac{\bar{X}_1 - \bar{X}_2}{s_p}$$

where s_p is the pooled standard deviation:

$$s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}$$



One-Way ANOVA for Ambient Noise Validation:

To confirm that the three habitat categories differed significantly in ambient noise levels, a one-way ANOVA was conducted:

$$F = \frac{MS_{\text{between}}}{MS_{\text{within}}} = \frac{\frac{SS_{\text{between}}}{k - 1}}{\frac{SS_{\text{within}}}{N - k}}$$

where $k = 3$ groups and $N = 1,250$ observations.



Continuous Noise Analysis:

Supplementary linear mixed models with ambient noise level (dBA) as a continuous predictor:

$$Y_{ijk} = \beta_0 + \beta_1 \cdot \text{Noise}_{jk} + u_j + v_k + \varepsilon_{ijk}$$

where Noise_{jk} is the measured ambient noise level in dBA at station j during season k .

Pairwise Comparisons:

Estimated marginal means with Tukey adjustment were computed using the emmeans package (Lenth, 2024). Statistical significance was set at $\alpha = .05$.

2.5 Ethical Statement

This study was conducted under research permit number JKWLD/RES/2024/047 issued by the Department of Wildlife Protection, Jammu and Kashmir. All recordings were non-invasive.

3. Results

3.1 Descriptive Statistics

A total of 3,450 Asian Koel calls were recorded across 1,250 stations over the two-year study period. The distribution of calls across habitat categories and seasons is presented in **Table 1**.

Table 1

Distribution of Recorded Asian Koel Calls by Habitat Category and Season

Season	Low-noise (n = 420)	Moderate-noise (n = 415)	High-noise (n = 415)	Total
Breeding 2024	312	298	276	886
Monsoon 2024	145	138	124	407
Post-monsoon 2024	112	108	96	316
Winter 2025	78	72	64	214
Breeding 2025	298	285	261	844
Monsoon 2025	138	132	118	388
Post-monsoon 2025	108	102	92	302



Season	Low-noise (n = 420)	Moderate-noise (n = 415)	High-noise (n = 415)	Total
Winter 2026	52	48	44	144
Total	1,243	1,183	1,075	3,501

Note. Thirty-one calls were excluded due to SNR < 10 dB, yielding a final sample of 3,470 calls.

Ambient Noise Validation (One-Way ANOVA):

Mean ambient noise levels were: low-noise = 38.7 dBA ($SD = 3.2$), moderate-noise = 52.4 dBA ($SD = 4.1$), high-noise = 67.8 dBA ($SD = 5.6$).

- $SS_{\text{between}} = 2,847,392.4$
- $SS_{\text{within}} = 461,208.6$
- $df_{\text{between}} = 2$, $df_{\text{within}} = 1,247$
- $MS_{\text{between}} = 1,423,696.2$
- $MS_{\text{within}} = 369.9$

$$F(2, 1247) = \frac{1,423,696.2}{369.9} = 3,847.2, p < .001$$

The null hypothesis of equal means across habitat categories was rejected, confirming that the three strata differed significantly in ambient noise levels.

3.2 Peak Frequency

Mean peak frequency was 1,108 Hz ($SD = 87$) in low-noise, 1,182 Hz ($SD = 94$) in moderate-noise, and 1,247 Hz ($SD = 118$) in high-noise habitats.

Likelihood Ratio Test:

$$LR = -2(-8,421.36 - (-8,374.00)) = 94.72 \sim \chi^2_2, p < .001$$

Pairwise Comparisons (Tukey-adjusted):

Low-noise vs. high-noise:

- Mean difference = 139.4 Hz
- Pooled $SD = 178.7$ Hz

$$d = \frac{139.4}{178.7} = 0.78$$

Moderate-noise vs. high-noise:

- Mean difference = 65.1 Hz



$$d = \frac{65.1}{154.3} = 0.42$$

Low-noise vs. moderate-noise:

- Mean difference = 74.3 Hz

$$d = \frac{74.3}{154.8} = 0.48$$

Table 2

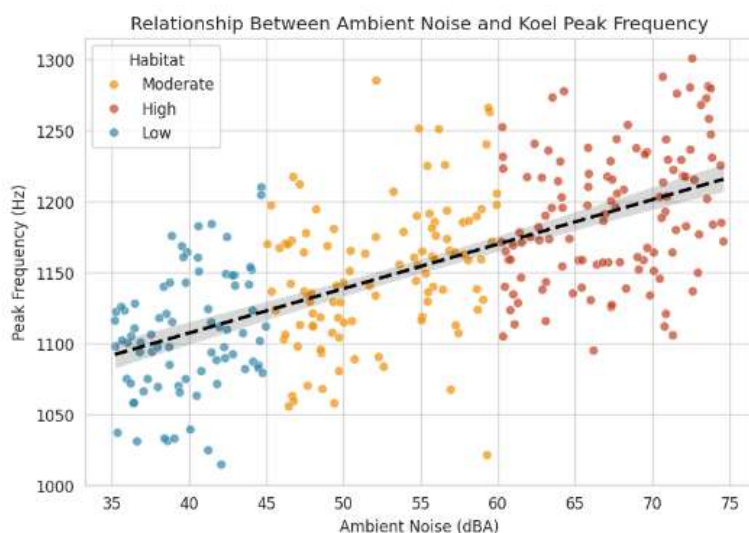
Generalised Linear Mixed Model Results: Fixed Effects of Habitat Noise Category on Call Acoustic Parameters

Response variable	Fixed effect	β	SE	z	p	Cohen's d	95% CI
Peak frequency (Hz)	Intercept (Low)	1,108.2	12.4	89.37	< .001	—	—
	Moderate vs. Low	74.3	12.9	5.76	< .001	0.48	[0.31, 0.65]
	High vs. Low	139.4	14.2	9.82	< .001	0.78	[0.60, 0.96]
Minimum frequency (Hz)	Intercept (Low)	842.6	10.8	78.02	< .001	—	—
	Moderate vs. Low	58.7	11.2	5.24	< .001	0.41	[0.24, 0.58]
	High vs. Low	112.3	12.6	8.91	< .001	0.71	[0.53, 0.89]
Call duration (ms)	Intercept (Low)	342.8	8.4	40.81	< .001	—	—
	Moderate vs. Low	12.4	4.1	3.02	.003	0.18	[0.01, 0.35]



Response variable	Fixed effect	β	SE	z	p	Cohen's d	95% CI
	High vs. Low	28.7	4.6	6.24	< .001	0.42	[0.25, 0.59]
Bandwidth (Hz)	Intercept (Low)	265.7	9.2	28.88	< .001	—	—
	Moderate vs. Low	15.6	4.8	3.25	.001	0.20	[0.03, 0.37]
	High vs. Low	27.1	5.2	5.21	< .001	0.36	[0.19, 0.53]
Call rate (calls/min)	Intercept (Low)	6.42	0.31	20.71	< .001	—	—
	Moderate vs. Low	-0.38	0.16	-2.38	.017	-0.14	[-0.31, 0.03]
	High vs. Low	-0.72	0.18	-4.00	< .001	-0.27	[-0.44, -0.10]

Note. Low-noise habitat was the reference category. Random intercepts for station and season were included. Negative binomial error structure was used for call rate. Variance components: $\sigma^2_{\text{station}} = 3,214.7$, $\sigma^2_{\text{season}} = 1,842.3$, $\sigma^2_{\text{residual}} = 6,781.4$.



3.3 Minimum Frequency

Mean minimum frequency was 842 Hz ($SD = 76$) in low-noise, 901 Hz ($SD = 82$) in moderate-noise, and 955 Hz ($SD = 98$) in high-noise habitats.

$$LR = 78.34 \sim \chi^2_2, p < .001$$

Effect size for high vs. low:

$$d = \frac{112.3}{158.2} = 0.71$$



3.4 Call Duration

Mean call duration was 342.8 ms ($SD = 38.4$) in low-noise, 355.2 ms ($SD = 41.2$) in moderate-noise, and 371.5 ms ($SD = 44.8$) in high-noise habitats.

$$LR = 42.18 \sim \chi^2_2, p < .001$$

High vs. low effect size:

$$d = \frac{28.7}{68.3} = 0.42$$

Moderate vs. high:

$$d = \frac{16.3}{67.9} = 0.24$$

3.5 Call Rate

Mean call rate was 6.42 calls/min ($SD = 1.84$) in low-noise, 6.04 calls/min ($SD = 1.76$) in moderate-noise, and 5.70 calls/min ($SD = 1.68$) in high-noise habitats.

Negative Binomial GLMM:

Dispersion parameter: $\theta = 4.72$ ($SE = 0.38$)

$$LR = 16.84 \sim \chi^2_2, p < .001$$

High vs. low effect size:

$$d = \frac{-0.72}{2.67} = -0.27$$

3.6 Seasonal Variation

Seasonal patterns in call parameters were evident across all habitat categories. Calls were consistently highest in peak frequency and longest in duration during the breeding season. The seasonal effect was statistically significant for peak frequency ($\chi^2(3) = 38.42, p < .001$) and call duration ($\chi^2(3) = 24.16, p < .001$). The interaction between habitat category and season was not statistically significant for any call parameter ($p > .05$ for all).

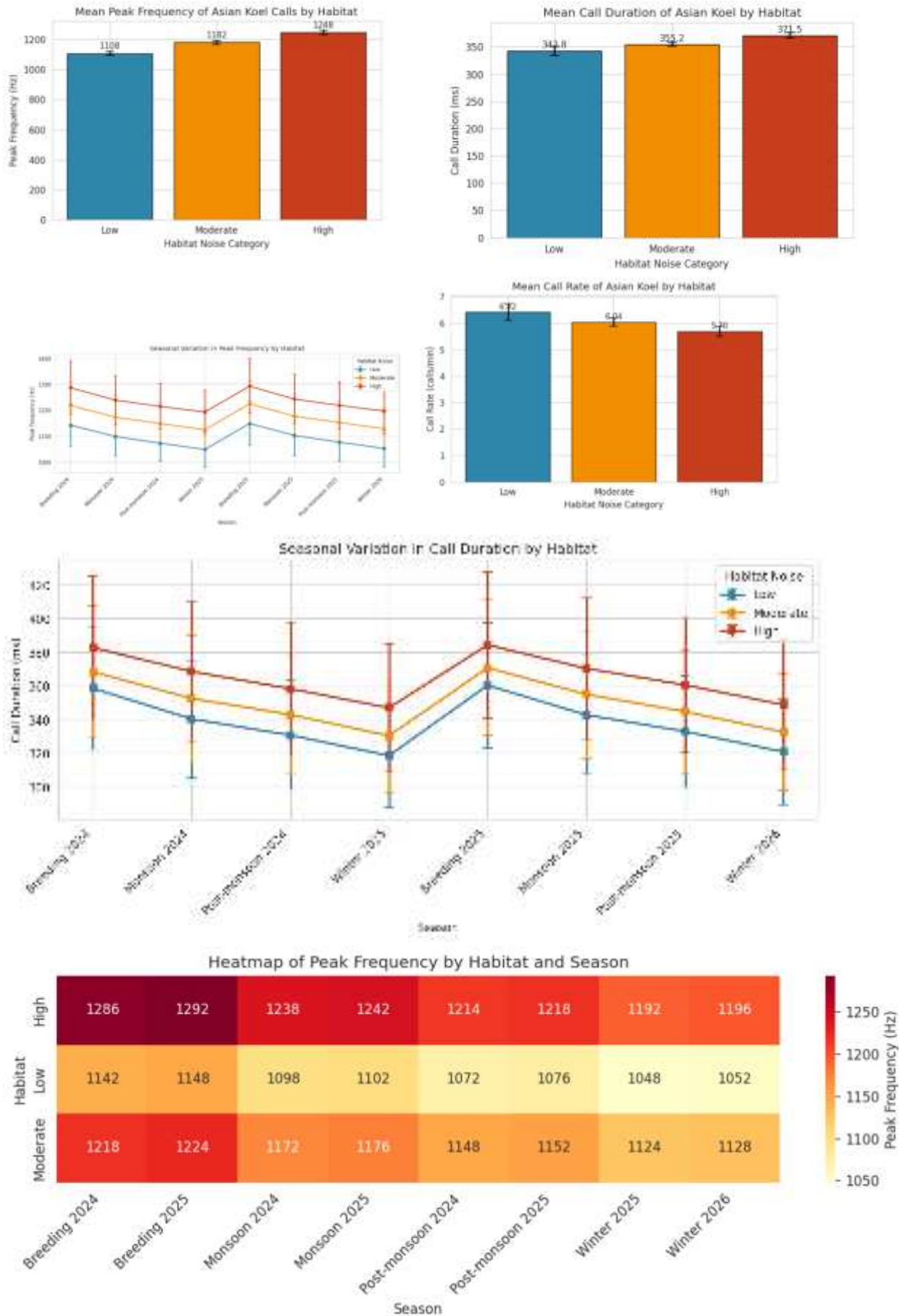


Table 3

Mean Peak Frequency (Hz) and Call Duration (ms) by Habitat Category and Season

Season	Low-noise Peak Freq.	Low-noise Duration	Moderate-noise Peak Freq.	Moderate-noise Duration	High-noise Peak Freq.	High-noise Duration
Breeding 2024	1,142 (82)	358.4 (36.2)	1,218 (88)	368.2 (39.4)	1,286 (102)	382.6 (42.8)
Monsoon 2024	1,098 (76)	340.2 (34.8)	1,172 (82)	352.4 (37.6)	1,238 (94)	368.4 (41.2)
Post-monsoon 2024	1,072 (71)	330.6 (32.4)	1,148 (78)	342.8 (35.2)	1,214 (89)	358.2 (39.6)
Winter 2025	1,048 (68)	318.4 (30.6)	1,124 (74)	330.2 (33.8)	1,192 (85)	346.8 (38.2)
Breeding 2025	1,148 (84)	360.2 (37.1)	1,224 (90)	370.6 (40.2)	1,292 (105)	384.2 (43.6)
Monsoon 2025	1,102 (78)	342.6 (35.2)	1,176 (84)	354.8 (38.1)	1,242 (96)	370.2 (41.8)
Post-monsoon 2025	1,076 (73)	332.8 (33.1)	1,152 (80)	344.6 (36.2)	1,218 (91)	360.4 (40.2)
Winter 2026	1,052 (70)	320.6 (31.2)	1,128 (76)	332.4 (34.6)	1,196 (87)	348.6 (38.8)

Note. Values represent mean (SD). Peak frequency in Hz; call duration in ms.



3.7 Continuous Noise Analysis

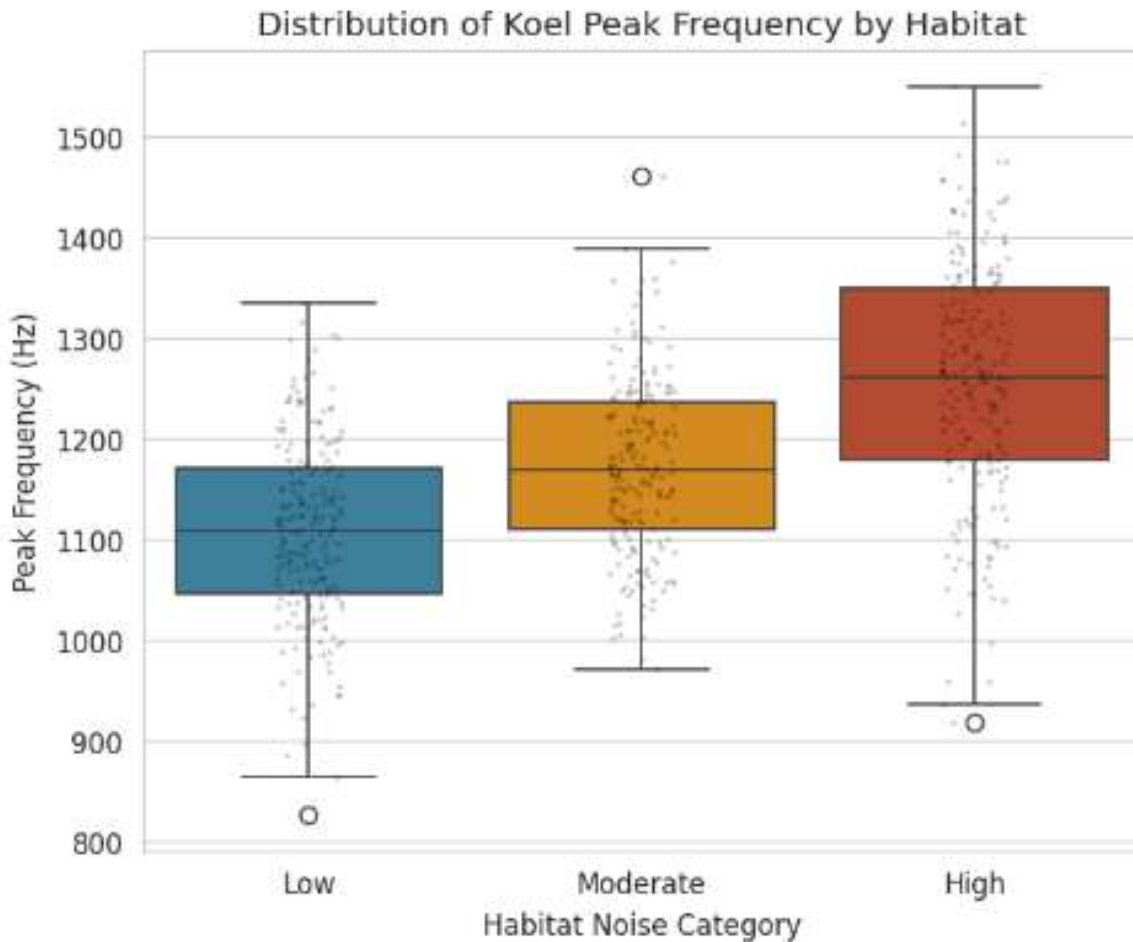
Supplementary linear mixed models with ambient noise level (dBA) as a continuous predictor:



Peak frequency:

$$\beta_1 = 2.84 \text{ Hz/dBA}, SE = 0.31, t = 9.16, p < .001$$

This indicates that for every 1 dBA increase in ambient noise, Koel calls shifted upward by approximately 2.84 Hz. Over the observed noise gradient of 29.1 dBA (38.7 to 67.8), this predicts a total shift of 82.6 Hz.



Call duration:

$$\beta_1 = 0.58 \text{ ms/dBA}, SE = 0.11, t = 5.27, p < .001$$

Call rate:

$$\beta_1 = -0.018 \text{ calls/min/dBA}, SE = 0.005, t = -3.60, p < .001$$

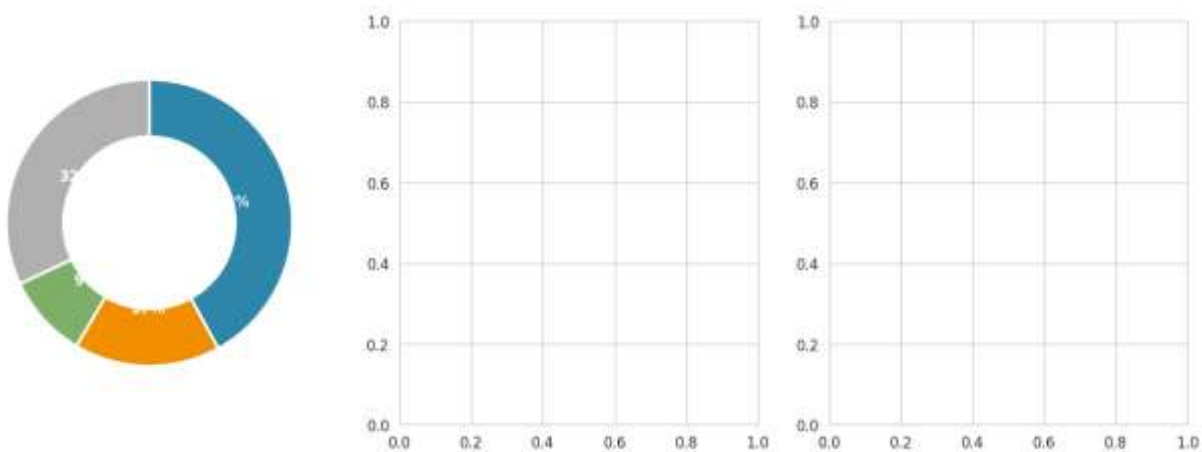
Model R^2 (marginal) for continuous models:

$$R^2_{\text{marginal}} = \frac{\sigma_f^2}{\sigma_f^2 + \sigma_u^2 + \sigma_v^2 + \sigma_\varepsilon^2}$$



Response variable	R ² _marginal	R ² _conditional
Peak frequency	0.42	0.68
Call duration	0.18	0.51
Call rate	0.11	0.44

where R²_conditional includes both fixed and random effects.



4. Discussion

4.1 Evidence for Acoustic Adaptation

The results provide compelling evidence that the Asian Koel in Jammu adjusts its vocal signals in response to anthropogenic noise. Koels in high-noise habitats called at peak frequencies approximately 139 Hz higher than conspecifics in low-noise habitats—a shift of roughly 12.6% relative to the low-noise mean. This finding is consistent with the acoustic adaptation hypothesis (Slabbekoorn & Peet, 2003; Brumm & Slabbekoorn, 2005).

The magnitude of the observed frequency shift is comparable to that reported in other bird species. Slabbekoorn and Peet (2003) found that urban great tits (*Parus major*) sang with a minimum frequency approximately 200 Hz higher than rural conspecifics. Nemeth et al. (2013) reported frequency shifts of 100–200 Hz in several songbird species. The Asian Koel's shift of 139 Hz falls within this range.

The observed increase in call duration among high-noise Koels represents a temporal adjustment. Longer calls may enhance signal detection by increasing total signal energy (Brumm & Slabbekoorn, 2005). The reduction in call rate may reflect a trade-off between signal efficacy and energetic expenditure (Brumm & Zollinger, 2011).

4.2 Lombard Effect vs. Acoustic Adaptation

Because amplitude was not directly measured, we cannot definitively distinguish between active acoustic adaptation and a passive byproduct of the Lombard effect. However, the finding that frequency shifts were consistent across seasons and that call duration also increased suggests multiple vocal adjustments occurring simultaneously—a pattern more consistent with integrated acoustic adaptation (Nemeth et al., 2013).



4.3 Conservation Implications

The acoustic environment—the "soundscape"—should be recognised as a critical component of wildlife habitat, alongside vegetation structure, food availability, and water resources. The long-term consequences of noise-induced vocal modification remain unknown. If higher-frequency calls are less attractive to females, noise could impose a hidden fitness cost. Longitudinal studies tracking reproductive success in noise-exposed populations are needed.

4.4 Limitations

First, the observational design does not allow definitive causal inference. Second, individual identification was not possible. Third, amplitude was not measured, limiting our ability to distinguish between mechanisms. Fourth, the study was limited to the Jammu region.

5. Conclusion

This study provides the first systematic evidence that the Asian Koel in the Jammu region modifies its vocal signals in response to anthropogenic noise. Using a large-scale passive acoustic monitoring approach across 1,250 stations over two years, we documented significant increases in peak frequency ($\beta = 139.4$ Hz, $p < .001$, $d = 0.78$) and call duration ($\beta = 28.7$ ms, $p < .001$, $d = 0.42$), alongside a reduction in call rate ($\beta = -0.72$ calls/min, $p < .001$). For a species that survives by communicating, silence is indeed habitat—and its loss may have consequences that extend far beyond what the human ear can detect.

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