PASSIVE ACOUSTIC MONITORING : ESTIMATING POPULATION DENSITY

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BACKGROUND

Passive acoustic monitoring (PAM) using **autonomous recording units** (ARUs) enables continuous, standardised biodiversity surveys at scales not achievable with traditional field methods. **Automated classifiers** such as BirdNET provide confidence scores for species detections, but these scores do not directly translate into ecological metrics. Given that classifier performance varies across sites and soundscapes, converting scores into reliable indicators such as call density (measure of vocal species abundance) requires careful calibration. This study develops and evaluates quantile-binning calibration methods to produce robust, threshold-free call density estimates for ecological monitoring.

OBJECTIVES

- Determine whether call density can be estimated reliably without using arbitrary detection thresholds.
- Robustness Across Strata: Evaluate whether 3 alternative calibration strategies called Strategies 1,2 and 3 remain stable when score distributions shift across audio sampling rate strata (32 kHz and 48 kHz) and how they compare to the study-level (overall study wide estimation).
- Ecological Validity: Assess whether estimated call-density patterns match ecological expectations for species' activity and distribution.

METHODOLOGY

- **Quantile Binning:** Scores transformed to logit scale and grouped into 3-6 quantile bins to segment the score distribution (Quantiles shown in yellow in figure below).
- **Annotation:** A subset of audio clips in each bin was manually validated by an Ornithologist.
- **Call density Estimation:** Per bin call density estimated using Beta-Binomial Model. Study level call density is the summation of per bin call density weighted by bin weight. Uncertainty is quantified using bootstrapping and repeated simulations techniques for model and validation uncertainty respectively.
- **Strategies - level Estimation:** Three strategies used to estimate call density when score distribution shifts between study level and stratum (32 kHz and 48 kHz audio sampling rate).
    - Strategy 1: Re-weight study level model with strata level bin weights.
    - Strategy 2: Use Kullback–Leibler divergence between study level and strata level distribution.
    - Strategy 3: Geometric mean of strategy 1 and 2.

Below is a figure of the methodology schematic process process of call density estimation. Section labeled **A** shows study level approach and section labeled **B** shows strata level approach.

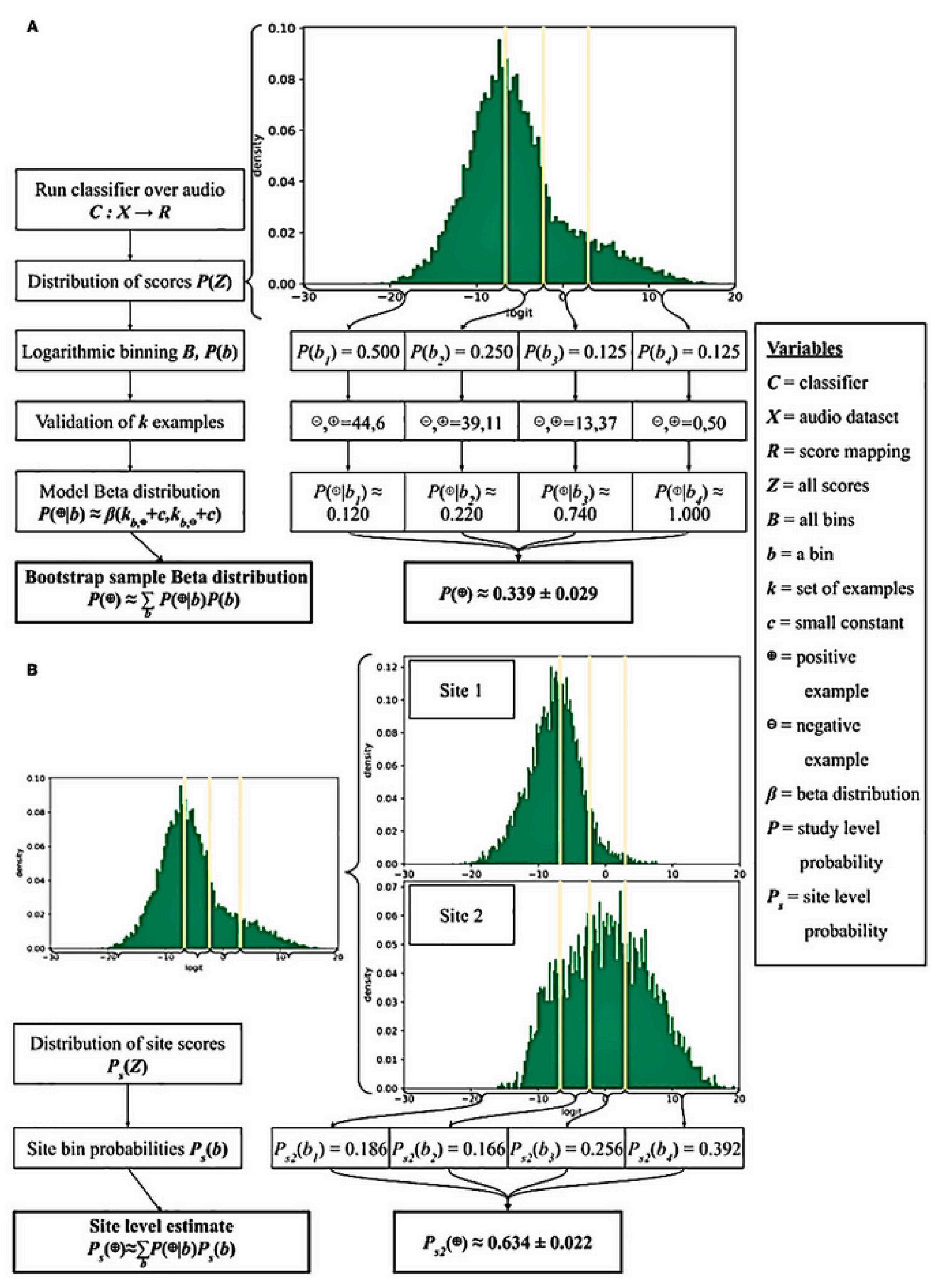

Figure 1 : A schematic of our direct call density estimation method at (A) the study-level using validation scheme chosen and (B) the site or covariate-level using computational Strategy 1.

RESULTS/FINDINGS

Data:
Five species of bird were analysed in this study. Namely they are; Baglafecht weaver, White-browed Coucal, African Gray Flycatcher, Abyssinian/Montane Nightjar and the African Pipit.

Plot:
Figure below is a results from the study of Abyssinnian/Montane Nightjar bird species. Results shown has **k** from figure 1 being 75 and shows results between two stratum (32 kHz and 48 kHz audio sampling rate). The error bars represent bootstrap standard deviation for the study level and strategy level estimates.

Relative Bias shows relative proportion by which call density estimate differs from actual observed density from all annotated samples.

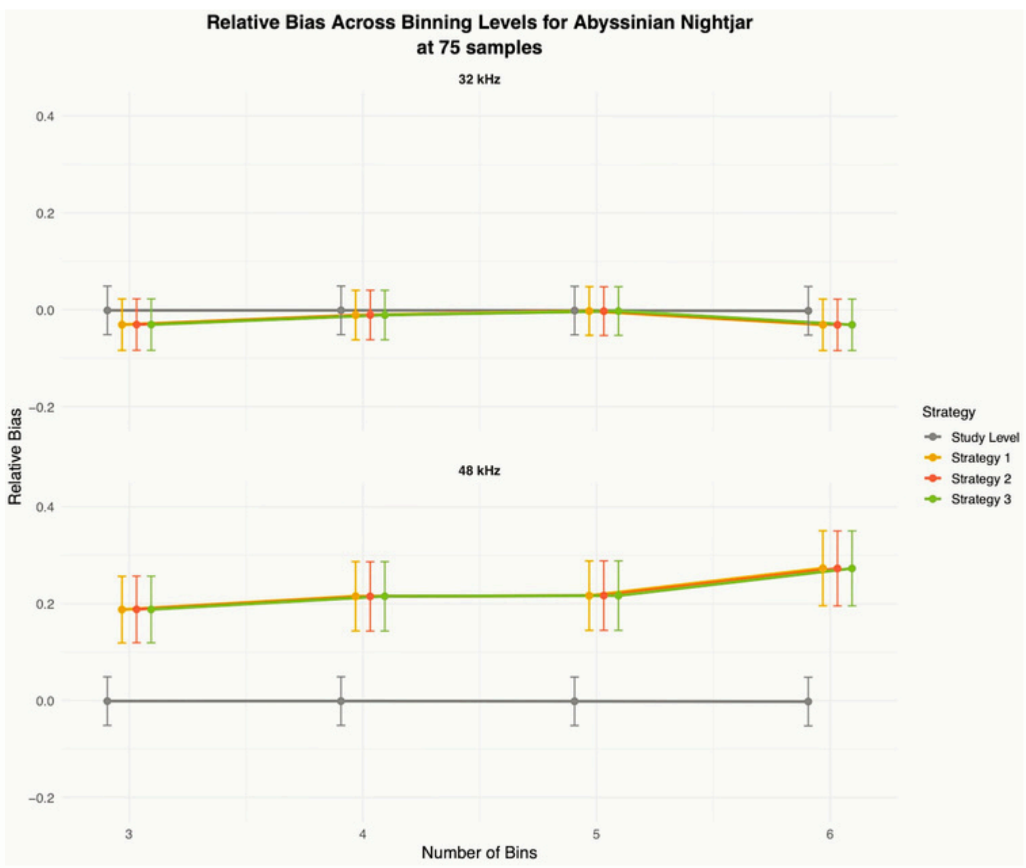

Figure 2: Relative Bias plot of Abyssinian/Montane nightjar species for all bins with 75 validation samples per bin used.

Results from the study:

- Study-level calibrations are most reliable, giving the lowest bias and variability across species, binning schemes, sampling rates, and validation depths.
- Strata-level strategies (1–3) behaved similarly to each other and rarely improved on the study-level model, often showing larger bias and variance, especially at 48 kHz and at extreme bin counts.
- Bin and sampling-rate effects were species-specific: Nightjar estimates were very stable, while Baglafecht, White-browed Coucal, African Grey Flycatcher, and African Pipit showed stronger distortions at certain bin counts and strata.
- Increasing validation effort (25 → 50 → 75 samples per bin) consistently improved performance, with strata-level estimates gradually converging toward the stable study-level estimates.

DISCUSSION

- **Study-level calibration performs strongly,** producing accurate and stable call-density estimates across species and binning schemes, with errors decreasing as validation sample sizes increase.
- **Strata-level strategies perform poorly:**
    - Strategies 1 and 2 fail to meaningfully correct distribution shifts between 32 kHz and 48 kHz.
    - Strategy 3 simply averages the shared biases of the first two approaches.
    - Sampling-rate effects are clear, with 48 kHz strata showing substantially higher bias due to sparse validated data.
- **Ecological interpretation remains limited**, as estimated call densities are uniformly low across species, driven primarily by heavy data loss and reconstruction during pre-processing, despite strong methodological performance at the study level.

CONCLUSION

- Study-level calibration is accurate and robust, performing consistently across species and binning schemes and confirming that threshold-free call-density estimation works well when bins are sufficiently populated.
- All strata-level strategies fail to accurately estimate call density under 32 kHz vs 48 kHz distribution shifts, producing large, inconsistent biases and offering no improvement over pooled study-level estimates.
- Ecologically, species-level patterns appear plausible, but absolute densities are severely deflated due to data reconstruction and negative-label dominance, indicating that strata-level methods require substantial refinement and careful implementation before supporting reliable spatial or sensor-specific inference.

REFERENCES:

Figure 1: Navine, C., Fiske, I., Sethi, S., Kahl, S., & Klinck, H. (2024). All thresholds barred: Direct estimation of call density in bioacoustic data. Frontiers in Bird Science, 3, 1380636.