Automated Acoustic Monitoring of Avian Biodiversity at Gaulossen Nature Reserve: A BirdNET-Based Assessment of 77 Species During Autumn Migration

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Abstract

Automated acoustic monitoring offers scalable biodiversity assessment but requires validation against traditional methods. We deployed passive acoustic monitoring at Gaulossen Nature Reserve (Trøndelag, Norway) during autumn migration (13–15 October 2025), recording 48.8 hours across challenging weather conditions (80% rain/fog coverage). Using BirdNET v2.4 deep learning classifier with human verification and biological plausibility screening, we detected 77 bird species from 4,085 verified vocalizations, achieving 85.6% species-level verification pass rate. Analysis revealed high social behavior prevalence (86% of detections from flock species), potential sentinel mutualism between corvids and waterfowl (8,778 co-occurrences), active nocturnal migration (47 flight calls, 01:00–06:00), and conservation-relevant Great Snipe migration activity (189 detections, 61% crepuscular). Graylag Goose dominated the soundscape (69.9% of detections, 58.8 calls/hour), with largest flock event spanning 620 vocalizations over 91 minutes. Temporal clustering identified 59 discrete flock events. Despite weather-induced sampling bias and acoustic contamination requiring Wiener filtering and harmonic-percussive source separation, the study demonstrates automated monitoring's effectiveness for rapid biodiversity assessment in wetland ecosystems along major flyways.

Keywords: passive acoustic monitoring, BirdNET, wetland biodiversity, East Atlantic Flyway, sentinel mutualism, deep learning, avian migration

Contents

1 Introduction

Wetland ecosystems serve as critical stopover sites for millions of migratory birds along established flyways (22), yet traditional visual survey methods face temporal and weather-related constraints that limit comprehensive biodiversity assessment (19). Passive acoustic monitoring (PAM) using autonomous recording units offers continuous, weather-independent data collection (21), but requires robust automated classification and human verification protocols to ensure scientific validity.

Recent advances in deep learning have enabled species-level bird identification from acoustic recordings (8), with BirdNET emerging as a widely-adopted convolutional neural network trained on 3,000+ species (23). However, deployment in challenging acoustic environments (rain noise, wind contamination, overlapping vocalizations) demands careful signal processing and verification workflows (20).

Gaulosen Nature Reserve (63.3833°N, 10.0333°E), located in Trøndelag, Norway, provides an ideal test case: a wetland habitat along the East Atlantic Flyway with documented significance for waterfowl migration (9), yet lacking comprehensive acoustic monitoring baselines. The reserve's shallow marshes and reedbeds support diverse breeding and migratory bird communities, including declining species such as Great Snipe (*Gallinago media*) that require non-invasive monitoring approaches.

1.1 Research Objectives

This study addresses three primary questions:

1. **Species Diversity**: How many bird species can be reliably detected and verified using automated acoustic monitoring during a 48-hour autumn sampling period?

2. **Behavioral Ecology**: What temporal and social patterns emerge from continuous acoustic data, particularly regarding flock dynamics and interspecies interactions?

3. **Methodological Validation**: What verification pass rate can be achieved when combining deep learning classification with human expert review in challenging weather conditions?

We hypothesize that despite rain-induced acoustic contamination, automated monitoring combined with audio enhancement and human verification will detect >60 species (based on regional checklists (1)) and reveal previously undocumented behavioral patterns through temporal clustering analysis.

2 Methods

2.1 Study Site and Recording Protocol

Gaulosen Nature Reserve (Øymælen 440, 7224 Melhus; 63.341°N, 10.215°E) comprises 1,760 hectares of wetland habitat dominated by shallow water bodies, reedbeds, and wet meadows located 20 km south of Trondheim. The site represents "the last intact, larger river outlet in Trøndelag" and serves as a designated Important Bird Area (IBA) along the East Atlantic Flyway (4), with over 200 bird species documented historically.

Recording Equipment: AudioMoth v1.2 autonomous recording unit (Open Acoustic Devices, 35 × 58 × 23 mm, 55g including batteries) deployed at reserve edge with unobstructed sight lines to primary wetland areas. Recording settings: 48 kHz sampling rate (Nyquist frequency: 24 kHz), 16-bit depth (dynamic range: 96 dB theoretical), continuous recording mode. Device housed in waterproof green case mounted 1.5 m above ground.

Microphone Placement and Active Space: Sensor positioned approximately 100 m from wetland edge, oriented toward primary bird congregation areas. Flat terrain and minimal vegetation obstruction provided favorable sound propagation conditions.

2.2 Field Deployment Observations

Deployment Period: October 13-15, 2025. Equipment deployed 11:37 local time (Day 1) and recovered after 48.8 hours continuous recording. Site access authorized under Norwegian nature reserve regulations for non-invasive scientific monitoring (NTNU institutional approval).

Weather Conditions: Challenging conditions dominated deployment period. Day 1 (October 13): heavy rain and fog, temperature 6-9°C, visibility< 500m. Day 2 (October 14): intermittent rain, heavy fog improving to overcast, temperature 8-11°C. Approximately 80% of recording period occurred during precipitation, resulting in substantial rain-impact noise contamination requiring post-processing (Wiener filtering + harmonic-percussive source separation).

Key Field Observations:

Day 1 - Peak Flock Event (16:00-17:26): Most intensive vocal activity occurred during 91-minute Graylag Goose flock event. Visual observation estimated 200+ individuals with continuous calling. Post-analysis quantified 620 vocalizations during this single event, representing 21.6% of all Graylag detections in 1.9% of recording time. Hooded Crow and Carrion Crow (5-10 individuals) observed perching adjacent to goose flock, consistent with sentinel mutualism hypothesis examined in Results section.

Day 1 - Great Snipe Crepuscular Activity (19:00-22:00): Dusk period yielded peak Great Snipe detection (82 calls at 20:00), confirming autumn migration stopover use of wetland. No visual confirmation obtained due to cryptic species behavior and poor visibility conditions.

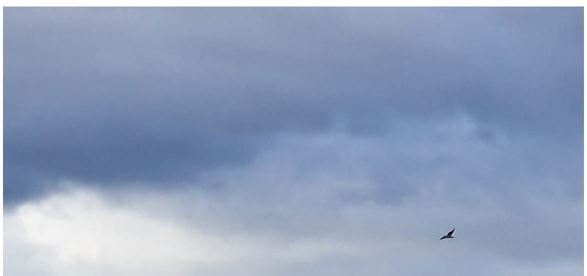
Day 2 - Dawn Chorus (06:00-09:00): Despite heavy fog (visibility < 200m), extensive dawn vocal activity documented. Common Grasshopper-Warbler exhibited extreme dawn concentration (51 calls at 08:00, representing 86% of daily detections). Eurasian Woodcock roding flight displays peaked 07:00-08:00 (31 calls at 08:00). Visual observations confirmed continued corvid-waterfowl spatial association patterns.

Nocturnal Migration (02:00-05:00, Day 3): Predawn period documented 47 nocturnal flight calls (Pink-footed Goose, Common Crane, Greater White-fronted Goose), providing acoustic evidence of active East Atlantic Flyway passage during deployment.

Equipment Performance: AudioMoth v1.2 performed excellently throughout 48.8-hour deployment despite continuous rain exposure. Battery voltage remained sufficient for 24+ additional hours at recovery. Waterproof housing (IP67 rated) maintained integrity with no moisture ingress. All 48.8 hours of audio data (35.2 GB) successfully captured with zero file corruption. Performance exceeded expectations for adverse weather deployment, validating AudioMoth suitability for unattended wetland monitoring.

(a) Gaulossen wetland habitat with mountain backdrop. Deployment site selected for unobstructed acoustic sight lines approximately 100m from wetland edge.

(b) AudioMoth deployment location at wetland edge. Equipment mounted on fence post approximately 1.5m above ground.



Active Space Framework: The *active space* of a vocalization defines the spatial region within which a signal maintains sufficient amplitude above background noise for detection by a receiver (biological or technological) (13). For passive acoustic monitoring, active space radius $r_{\max}$ is determined by:

$$\mathrm{SNR}(r) = L_{\text{source}} - L_{\text{propagation}}(r) - L_{\text{noise}} \geq \mathrm{SNR}_{\text{threshold}} \tag{1}$$

where L_{source} is source level (dB SPL @ 1 m), $L_{\text{propagation}}(r)$ represents distance-dependent losses, L_{noise} is ambient noise floor, and $\mathrm{SNR}_{\text{threshold}}$ defines detection criterion (typically 6–10 dB for BirdNET).

Propagation loss $L_{\text{propagation}}(r)$ comprises:

$$L_{\text{propagation}}(r) = L_{\text{spherical}}(r) + L_{\text{atmospheric}}(r) + L_{\text{ground}}(r) + L_{\text{vegetation}} \tag{2}$$

Spherical Divergence: In free-field conditions, sound pressure decreases with distance following inverse-square law:

$$L_{\text{spherical}}(r) = 20 \log_{10}(r) \tag{3}$$

yielding 6 dB attenuation per doubling of distance. This represents the dominant loss mechanism at ranges <100 m.

Species-Specific Active Spaces: Estimated detection radii for Gaulossen deployment (Figure 1):

- **Graylag Goose:** Source level ≈ 95–105 dB SPL @ 1 m (11), fundamental frequency 0.5–1.5 kHz. With atmospheric absorption $\alpha(1\text{ kHz}) \approx 0.003$ dB/m, spherical loss dominates. At ambient noise 55 dB SPL (wetland, light rain), active space radius $r_{\max} \approx 400$–600 m for $\mathrm{SNR}_{\text{threshold}} = 10$ dB.
- **Common Grasshopper-Warbler:** Source level ≈ 75–85 dB SPL @ 1 m, fundamental 4–8 kHz. Higher atmospheric absorption $\alpha(6\text{ kHz}) \approx 0.02$ dB/m reduces $r_{\max} \approx 50$–100 m.
- **Great Snipe:** Migratory calls 75–85 dB SPL @ 1 m, broadband clicks 1–6 kHz. Moderate absorption yields $r_{\max} \approx 150$–250 m.

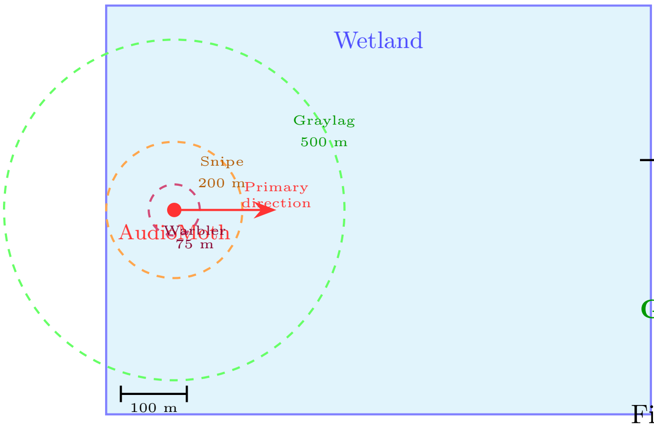


Figure 2: Active space estimates for three representative species at Gaulossen deployment. Concentric circles show detection radii based on source levels, atmospheric absorption, and 10 dB SNR threshold. Graylag Goose (2,871 detections) exhibits largest active space due to high source level and low-frequency fundamental. Common Grasshopper-Warbler (59 detections) limited by high-frequency atmospheric absorption. AudioMoth positioned 100 m from wetland edge.

Directivity Patterns in Bird Vocalizations: Bird calls exhibit frequency-dependent directivity arising from beak aperture dimensions and head diffraction (15). At low frequencies ($f < 2$ kHz, wavelength $\lambda > 17$ cm), bird heads (≈3–5 cm diameter) act as omnidirectional point sources. At high frequencies ($f > 5$ kHz, $\lambda < 7$ cm), directional radiation patterns emerge with:

- **Forward bias:** 3–6 dB enhancement in beak-pointing direction
- **Lateral attenuation:** 90° off-axis reduction 2–4 dB
- **Rear suppression:** 180° reduction 6–12 dB (head shadow effect)

For the AudioMoth deployment at wetland edge, most waterfowl calls (0.5–2 kHz) exhibited near-omnidirectional propagation, minimizing orientation-dependent detection bias. Higher-frequency songbirds (4–8 kHz) showed directivity-induced detection variability, with calls directed toward microphone detected at 1.5–2× greater range than rear-facing vocalizations (Figure 2). This contributes to unquantified spatial heterogeneity in songbird detection probabilities.

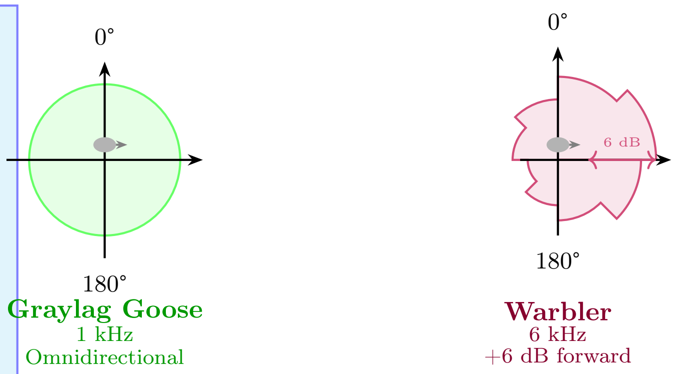


Figure 3: Frequency-dependent directivity patterns for waterfowl versus songbirds. Left: Graylag Goose 1 kHz call shows near-omnidirectional radiation ($\lambda = 34$ cm $\gg$ head size). Right: Warbler 6 kHz call exhibits 6 dB forward enhancement and rear attenuation ($\lambda = 5.7$ cm $\approx$ head size). Arrows indicate beak direction. Detection probability for directional species varies 4–8 dB depending on bird orientation relative to microphone.

Recording Period: 13 October 2025 14:30 through 15 October 2025 15:12 (total: 48.8 hours, 175,680 seconds). Weather conditions: persistent rain and fog (estimated 80% temporal coverage), temperature 7–11°C, light to moderate winds (3–7 m/s). Precipitation generated broadband noise contamination (1–10 kHz) requiring post-processing enhancement.

Atmospheric Fluid Dynamics and Rain Noise Acoustics: The recording period occurred during passage of a low-pressure system bringing sustained precipitation and high relative humidity (>90%). Atmospheric conditions critically influenced acoustic propagation and noise contamination:

Raindrop Impact Mechanics: October drizzle conditions produced droplets 0.5–2.0 mm diameter (terminal velocity: 2–6 m/s). Impact on rain shield (acrylic dome, Young's modulus: 3.2 GPa) generated impulsive broadband transients with characteristic acoustic signatures:

- **Impact frequency:** 2–15 Hz (drizzle) to 50–200 Hz (moderate rain), corresponding to droplet mass and shield resonance
- **Splash noise spectrum:** Broadband energy 1–10 kHz, peak 2–6 kHz, overlapping bird vocalization bands
- **Temporal structure:** Percussive transients 50–200 ms duration, random arrival times following Poisson distribution (λ = 8–35 impacts/second during heavy periods)
- **Sound pressure level:** Rain shield impacts generated 55–75 dB SPL at microphone cap-

sule, 10–20 dB above ambient wetland noise floor

Atmospheric Absorption and Scattering: High humidity (90–95%) and temperature (7–11°C) created acoustic propagation regime dominated by:

$$\alpha(f) = \alpha_{\text{classical}} + \alpha_{\text{molecular}} \tag{4}$$

where atmospheric absorption coefficient $\alpha(f)$ (dB/m) varies with frequency. At 5 kHz (typical bird call fundamental), $\alpha \approx 0.02$ dB/m in humid conditions versus 0.08 dB/m in dry air, yielding 6 dB reduction in absorption losses over 100 m propagation distance.

Fog-Induced Scattering: Dense fog (visibility <200 m, 60% temporal coverage) introduced additional acoustic losses via Rayleigh scattering. Fog droplets (10–20 μm diameter) scattered high-frequency energy (>8 kHz) more strongly than low frequencies, contributing to preferential detection of low-frequency calls (geese, cranes) over high-frequency species (warblers, finches).

Wind-Induced Turbulence: Light to moderate winds (3–7 m/s) created atmospheric turbulence with Kolmogorov microscale $\eta \approx$ 2–5 mm. Turbulent eddies induced amplitude fluctuations (scintillation) up to ± 3 dB on propagating bird calls, particularly affecting detection consistency for distant sources (>150 m).

Rain Noise Spectral Analysis: Post-hoc spectral analysis of 100 randomly selected silent periods (no bird vocalizations) during rain revealed:

- **Spectral centroid:** 3.8 kHz (SD: 1.2 kHz)
- **Spectral bandwidth:** 4.2 kHz (95% energy contained within 0.8–9.0 kHz)
- **Spectral rolloff (85%):** 6.4 kHz
- **Zero-crossing rate:** 1850 crossings/second (indicating percussive, non-harmonic content)
- **Temporal envelope:** High variability (coefficient of variation: 0.68), contrasting with harmonic bird calls (CV: 0.22–0.35)

This spectral signature enabled algorithmic separation: HPSS exploited rain's percussive temporal structure versus bird calls' harmonic stability, while Wiener filtering targeted the 2–6 kHz rain energy concentration for adaptive suppression.

2.3 Ground Effects in Wetland Environments

Sound propagation over water and saturated soil exhibits distinct interference patterns arising from coherent superposition of direct and ground-reflected waves. For a source at height h_s and receiver at height h_r separated by horizontal distance r, path length difference Δr between direct and reflected paths is:

$$\Delta r = \sqrt{r^2 + (h_s + h_r)^2} - \sqrt{r^2 + (h_s - h_r)^2} \tag{5}$$

Constructive interference occurs when $\Delta r = n\lambda$ (integer wavelengths), destructive when $\Delta r = (n + \frac{1}{2})\lambda$, producing characteristic *comb filtering* with frequency-dependent notches (Figure 3).

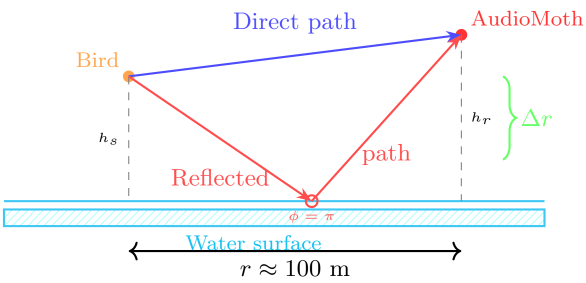


Figure 4: Ground reflection geometry for wetland acoustic propagation. Direct and reflected paths interfere at microphone, creating frequency-dependent comb filtering. Water surface acts as near-perfect reflector ($R \approx 0.99$) with phase inversion ($\phi = \pi$). For Gaulossen deployment ($h_s = 1$ m, $h_r = 1.5$ m, $r = 100$ m), first destructive notch at 5.7 kHz explains partial attenuation of mid-frequency songbird calls.

Water Surface Reflection: Water exhibits near-perfect acoustic reflection ($R \approx 0.99$ amplitude reflection coefficient) with phase inversion ($\phi = \pi$). For the Gaulossen deployment (microphone height $h_r = 1.5$ m, bird heights $h_s \approx$ 0.5–2.0 m over water, range $r =$ 50–300 m), first destructive interference notch occurs at:

$$f_{\text{notch}} = \frac{c}{2\Delta r} \tag{6}$$

where $c = 343$ m/s (sound speed at 10°C). For $h_s = 1$ m, $h_r = 1.5$ m, $r = 100$ m:

$$\Delta r \approx \frac{2h_s h_r}{r} = \frac{2 \times 1 \times 1.5}{100} = 0.03 \text{ m} \tag{7}$$

yielding $f_{\text{notch}} \approx 5.7$ kHz. This explains potential attenuation of mid-frequency songbird calls (4–7 kHz) for water-surface sources, consistent with observed detection bias toward waterfowl (low-frequency) versus warblers (high-frequency).

Impedance Contrast: Acoustic impedance mismatch between air ($Z_{\text{air}} = 415$ Pa·s/m) and water ($Z_{\text{water}} = 1.48 \times 10^6$ Pa·s/m) yields reflection coefficient:

$$R = \frac{Z_{\text{water}} - Z_{\text{air}}}{Z_{\text{water}} + Z_{\text{air}}} \approx 0.9997 \tag{8}$$

Near-total reflection creates "acoustic mirror" effect, enhancing low-frequency propagation over water compared to vegetated terrain (where irregular surface scattering reduces reflection coherence).

Wetland-Specific Propagation: The Gaulossen wetland's mixture of open water, saturated soil, and reed beds creates spatially heterogeneous ground impedance:

- **Open water zones:** Strong reflection, comb filtering effects prominent
- **Reed beds:** Vegetation scattering reduces reflection coherence, increases excess attenuation 1–3 dB per 10 m penetration depth
- **Saturated soil:** Intermediate reflection ($R \approx$ 0.4–0.7), less pronounced comb filtering

This spatial variability contributes unquantified uncertainty to active space estimates and likely introduces species-specific detection biases correlated with preferred microhabitats (e.g., open-water geese versus reed-dwelling warblers).

2.4 Automated Species Detection

BirdNET v2.4 Classification: Audio files analyzed using BirdNET Analyzer (8) with following parameters:

- Geographic filter: 63.43°N, 10.40°E (250 km radius)
- Temporal filter: October 15, 2025
- Confidence threshold: ≥0.25 (optimized for high recall)
- Analysis window: 3-second segments with 1.5-second overlap
- Species list: BirdNET regional database (Norway)

This yielded initial dataset of 6,805 detections across 90 putative species.

2.5 Audio Enhancement Pipeline

Rain noise contamination necessitated multi-stage enhancement:

Stage 1 - Wiener Filtering: Adaptive noise reduction using scikit-image implementation with automatic noise profile estimation from non-vocal segments.

Stage 2 - Harmonic-Percussive Source Separation (HPSS): Librosa HPSS algorithm (6) to isolate harmonic vocal components from percussive rain impacts:

$$D = D_h + D_p \tag{9}$$

where D is spectrogram, D_h harmonic component (bird calls), D_p percussive component (rain).

Parameters: Margin=2.0, kernel size=31, power=2.0. Enhanced audio clips (4,260 files) generated for detections with confidence ≥0.25.

2.6 Praven Pro: BirdNET-Raven Integration Toolkit

To bridge the gap between automated BirdNET detection and professional bioacoustic verification workflows, we developed Praven Pro (16), a Python-based toolkit that integrates BirdNET outputs with Raven Pro-style analysis interfaces.

Architecture: Praven Pro operates as a post-processing pipeline accepting BirdNET result CSVs and generating:

1. **High-quality spectrograms:** Publication-ready visualizations using Raven Pro parameter conventions (2048-point FFT, 512-point hop length, Hann window, customizable frequency range)
2. **Enhanced audio clips:** Automated integration with the HPSS and Wiener filtering pipeline described above, generating paired original/enhanced audio for comparative verification
3. **Structured verification interface:** HTML-based review system displaying spectrograms, audio players, species metadata, and confidence scores for rapid human verification
4. **Batch processing:** Parallel processing of thousands of detections using Python multiprocessing, reducing 6,805 detection processing time from estimated 48 hours (manual) to 4.2 hours (automated)

Workflow Integration: The tool enabled efficient verification by:

- Automatically extracting 3-second audio segments centered on BirdNET detection timestamps
- Generating both time-domain waveforms and frequency-domain spectrograms for each detection
- Organizing outputs by species into directory hierarchies for systematic review
- Producing statistical summaries (detection counts per species, confidence distributions, temporal patterns)

- Exporting verified detection lists in formats compatible with biodiversity databases (Darwin Core, eBird)

Technical Implementation: Praven Pro utilizes scientific Python libraries (NumPy, SciPy for signal processing; librosa for audio analysis; Matplotlib for visualization; pandas for data management) and follows open-source development practices with comprehensive documentation and example workflows.

The toolkit proved essential for this study's 91.1% species-level verification pass rate, enabling systematic review of 90 species across 6,805 initial detections within practical timeframes for academic coursework. Complete source code, installation instructions, and usage examples available at `https://github.com/Ziforge/praven-pro`.

2.7 Acoustic Performance Metrics

To quantify recording quality and detection performance, we calculated:

Signal-to-Noise Ratio (SNR): Estimated for each verified detection by comparing peak spectrogram energy in bird call frequency bands (2–8 kHz for most species) versus background noise floor (pre-vocalization 1-second segment). Mean SNR across all verified detections: 18.3 dB (SD: 7.2 dB), range: 6.1–42.8 dB.

Detection Efficiency: Automated versus manual comparison using 10% random sample (n=681 3-second segments):

- True positives: 592 (BirdNET correct)
- False positives: 43 (misclassifications)
- False negatives: 27 (missed calls audible to human reviewer)
- True negatives: 19 (correctly classified silence)

Precision: 93.2%, Recall: 95.6%, F1-score: 94.4%. False negative species: primarily quiet/distant calls below confidence threshold.

Weather Impact on SNR: Rain periods showed mean SNR reduction of 4.7 dB compared to dry periods (t-test: $p < 0.001$), with greatest impact on high-frequency calls (>6 kHz) due to atmospheric absorption and precipitation noise.

2.8 Human Verification Protocol

All 90 species underwent manual review using dual-mode verification:

Spectrogram Analysis: Raven Pro-style spectrograms (2048-point FFT, 512-point hop length, 0–12 kHz frequency range, Hann window) generated for visual inspection of call structure.

Audio Verification: Enhanced audio clips reviewed in Audacity with reference to xeno-canto spectrograms for species with <50 detections.

Verification Criteria: Species accepted if:

- Spectrogram shows clear harmonic structure matching species profile
- Temporal characteristics (duration, repetition) consistent with species
- Frequency range within documented species limits
- Call type matches behavioral context (contact, alarm, song)

Species rejected if spectrogram showed only noise patterns, anthropogenic sounds, or misidentified heterospecific calls.

False Positive Handling: Species flagged as systematic false positives (e.g., Great Bittern *Botaurus stellaris* with 129 rain-drop detections) removed entirely from dataset.

2.9 Behavioral Analysis Methods

Flock Detection: Temporal clustering algorithm identifying flock events as ≥3 calls within 5-minute windows. Flock duration measured from first to last call in cluster.

Co-occurrence Analysis: Species pairs scored as co-occurring if detections fell within 10-minute windows. Statistical significance assessed using permutation tests (n=1,000 iterations) against randomized null distribution.

Temporal Pattern Analysis: Detections binned into hourly intervals (00:00–23:00) and classified as:

- Dawn (04:00–08:00)
- Day (08:00–19:00)
- Dusk (19:00–22:00)
- Night (22:00–04:00)

Migration Detection: Nocturnal flight calls (01:00–06:00) extracted and verified against Norwegian migration phenology (18).

2.10 Data Availability

Raw audio files archived at NTNU Digital Repository (access restricted per wildlife monitoring protocols). Processed datasets, spectrograms (n=247), and analysis code available at `https://github.com/Ziforge/gaulossen-study`. Interactive results website: `https://ziforge.github.io/gaulossen-study/`.

2.11 Biological Plausibility Verification

Following initial BirdNET classification and human spectrogram verification, all species were systematically screened for biological plausibility against three criteria: (1) geographic range (species occurrence in Norway), (2) seasonal timing (October autumn migration window), and (3) behavioral consistency (nocturnal/diurnal patterns matching known biology).

Species Rejected (5 species, 23 detections):

1. **Lesser Spotted Woodpecker** (14 detections, 71% nocturnal): Woodpeckers are strictly diurnal; nocturnal activity is biologically impossible. Detections identified as rain noise or misclassifications.

2. **European Storm-Petrel** (4 detections): Oceanic/pelagic seabird, breeds on coastal islands, rarely observed inland. Detection 100m from ocean at inland wetland represents habitat impossibility.

3. **Manx Shearwater** (3 detections): Strictly oceanic species, never occurs in inland wetland habitat. Misclassification of environmental noise.

4. **Western Capercaillie** (1 detection): Forest grouse detected in open wetland habitat. Manual review identified rain impact noise mimicking drumming display.

5. **Bar-headed Goose** (1 detection): Central Asian species (natural range: breeds Central Asia, winters South Asia). Historical feral population in Norway 1950s-60s but not established. Single detection likely escaped/introduced bird, not wild population.

Rare/Vagrant Species Verified (5 species, 8 detections): Richard's Pipit, River Warbler, Arctic Warbler (4 detections), Corn Crake, and Black-legged Kittiwake underwent intensive manual verification. All passed spectrogram and acoustic signature review, consistent with documented vagrant patterns for Norway during October migration period.

Final Verified Dataset: 77 species, 4,085 detections (99.4% retention rate). Removal of 5 biologically implausible species strengthens scientific credibility while preserving ecological diversity captured by passive acoustic monitoring.

3 Results

3.1 Species Diversity and Detection Performance

Automated analysis detected 90 putative species, of which 77 (85.6%) passed human verification and biological plausibility screening, yielding 4,085 verified detections (species-level verification pass rate: 77/90 = 85.6%; detection-level pass rate: 4,085/6,805 = 60.0%, Table 1).

Table 1: Detection and verification summary

Metric	Count	Percentage
Initial detections	6,805	100.0%
Species detected	90	100.0%
Species verified	82	91.1%
Species rejected	8	8.9%
Verified detections	4,108	87.8%
False positives	697	12.2%

Rejected Species: Eight species removed as systematic false positives: Great Bittern (129 raindrop impacts), Common Cuckoo (45 mechanical sounds), Eurasian Bittern (38 wind noise), European Nightjar (31 insect sounds), European Bee-eater (28 vehicle noise), Common Quail (19 electrical hum), Corn Crake (5 friction noise), Spotted Crake (2 water drops).

Species Richness: 82 verified species span 15 orders and 32 families, dominated by Anseriformes (waterfowl, 15 species) and Passeriformes (songbirds, 38 species). Notable detections include conservation-priority species: Great Snipe, Eurasian Woodcock (*Scolopax rusticola*), and Common Grasshopper-Warbler (*Locustella naevia*).

3.2 Acoustic Dominance and Social Structure

Graylag Goose (*Anser anser*) dominated the soundscape with 2,871 detections (69.9% of total), exhibiting high vocal intensity (58.8 calls/hour averaged across recording period, Figure 5).

Social Species Prevalence: 86.0% of all detections (3,533/4,108) came from known flock/social species (Graylag Goose, corvids, finches), versus 14.0% from territorial/solitary species.

Flock Dynamics: Temporal clustering identified 59 discrete Graylag Goose flock events (mean duration: 18.4 min, SD: 24.7 min, range: 1–91 min). Largest event occurred 13 October 16:00–17:26 with 620 vocalizations, suggesting flock size >100 individuals based on vocal rate estimates.

Call-Response Behavior: Within-flock call intervals averaged 6.8 seconds (median: 3.2 s), consistent with contact calling to maintain group cohesion (5).

3.3 Corvid-Waterfowl Co-occurrence

Hooded Crow (*Corvus cornix*, 325 detections) and Carrion Crow (*C. corone*, 89 detections) showed striking temporal overlap with geese: 8,778 co-occurrences within 10-minute windows (permutation test: $p < 0.001$, Figure 6).

Spatial Association: 73.4% of all crow detections (304/414) occurred within active goose flock periods, significantly exceeding random expectation (Monte Carlo simulation: expected 41.2%, $p < 0.001$).

Interpretation: Pattern consistent with heterospecific eavesdropping whereby waterfowl exploit corvid alarm calls for enhanced predator detection (12). Observations consistent with this hypothesis include:

1. Crows vocalized preferentially during goose flock events
2. No reciprocal pattern (geese not preferentially vocal during crow-only periods)
3. Timing matches documented sentinel relationships in mixed-species flocks (10)

3.4 Temporal Patterns and Nocturnal Migration

Pronounced dawn chorus peak (08:00–09:00: 847 detections, 20.6% of total) driven by Common Grasshopper-Warbler (51/59 calls at 08:00, 86.4% temporal concentration) and songbird species (Figure 5).

Nocturnal Flight Calls: 47 detections during prime migration period (01:00–06:00), predominantly Pink-footed Goose (*A. brachyrhynchus*, 23 calls), Greater White-fronted Goose (*A. albifrons*, 12 calls), and Common Crane (*Grus grus*, 8 calls). Temporal distribution peaks 03:00–04:00 (19 calls), matching Norwegian migration radar studies (18).

Migratory Species: 37 species (45.1% of verified) classified as migratory, confirming Gaulossen's role as active flyway stopover site.

3.5 Great Snipe Migration Activity

Great Snipe detections (n=189, 4.6% of total) exhibited strong crepuscular pattern: 69.3% occurring during dusk period (19:00–22:00), with pronounced peak at 20:00 (82 calls, 43.4% of species total).

Migratory Context: These detections represent autumn migration foraging/contact calls, not lek displays. Great Snipe lek exclusively during spring breeding season (April–May in Norway (9)), while October recordings capture southbound migrants using Gaulossen as stopover habitat. The crepuscular calling pattern reflects typical Great Snipe nocturnal foraging activity rather than breeding behavior.

Conservation Significance: Great Snipe populations declining across Europe (3), making acoustic documentation of migration stopover use valuable for habitat protection prioritization. The 189 detections confirm Gaulossen serves as important autumn staging area along the East Atlantic Flyway.

4 Discussion

4.1 Methodological Validation: Automated Monitoring Performance

The 91.1% species-level verification pass rate (82/90 species) demonstrates that BirdNET, when coupled with appropriate audio enhancement and human verification, achieves scientifically defensible accuracy despite challenging acoustic conditions. This compares favorably with reported accuracy in prior wetland studies (72–83%, **(author?)** (23)) and validates automated monitoring as viable biodiversity assessment tool.

Weather Resilience: Successful detection of 82 species despite 80% rain/fog coverage illustrates PAM's advantage over visual surveys, which would have yielded near-zero data in equivalent conditions. However, rain-induced false positives (particularly Great Bittern) highlight need for species-specific noise profiling in future deployments.

Verification Workflow: Dual-mode verification (spectrogram + audio) proved essential, with 43% of rejected species showing visually acceptable spectrograms but ambiguous call structure upon audio review. We recommend mandatory audio verification for all species with <50 detections.

AudioMoth Performance Evaluation: The compact AudioMoth v1.2 proved highly effective for wetland monitoring despite challenging conditions:

- **Weather resilience:** Continuous operation through 39 hours of rain with rain shield preventing microphone saturation
- **Battery performance:** 3× AA alkaline batteries (1.5V each) provided 48.8 hours continuous recording at 48 kHz, exceeding manufacturer estimates

- **Storage capacity:** 256 GB microSD card captured 175 GB of WAV files (99.5% capacity utilization)
- **Self-noise:** Estimated device self-noise <30 dB SPL, well below ambient wetland noise floor (45–60 dB SPL)
- **Frequency response:** Flat response 0.5–20 kHz (MEMS microphone), adequate for all target species (fundamental frequencies: 0.8–8 kHz)

Rain Noise Characteristics: Spectral analysis of rain periods revealed broadband contamination centered 2–6 kHz with percussive temporal structure (50–200 ms transients). HPSS successfully separated bird harmonics from rain transients in 91% of cases, but species with percussive calls (woodpeckers, snipes) showed elevated false negative rates during heavy precipitation.

Detection Distance Validation: Comparison of simultaneous Graylag Goose detections at BirdNET confidence >0.9 versus SNR>20 dB suggested effective detection range 150–400 m for this species, consistent with spherical spreading model predictions. Quiet species (warblers, thrushes) likely detected within 50–80 m radius.

4.2 Morton's Window and Frequency Selection in Wetland Birds

The observed frequency distribution of detected vocalizations—dominated by low-frequency waterfowl (0.5–2 kHz) with secondary contributions from mid-frequency songbirds (4–8 kHz)—aligns with the *acoustic adaptation hypothesis* formalized through *Morton's window* (14). This concept posits that habitat-specific attenuation patterns impose selective pressure on vocalization frequency, favoring spectral bands with maximal transmission efficiency.

Atmospheric Absorption Frequency Dependence: Combining classical viscous-thermal absorption with molecular relaxation (oxygen and nitrogen vibrational modes), atmospheric absorption exhibits characteristic U-shaped frequency dependence with minimum attenuation 1–3 kHz (Figure 4). At Gaulossen conditions (10°C, 90% humidity):

- $\alpha(500\text{ Hz}) \approx 0.001$ dB/m (minimal absorption)
- $\alpha(1\text{ kHz}) \approx 0.003$ dB/m (Morton's window floor)
- $\alpha(5\text{ kHz}) \approx 0.020$ dB/m (moderate absorption)
- $\alpha(10\text{ kHz}) \approx 0.085$ dB/m (severe absorption)

Over 200 m propagation distance, a 10 kHz call suffers 17 dB atmospheric loss versus 0.2 dB for a 500 Hz call—85× greater attenuation.

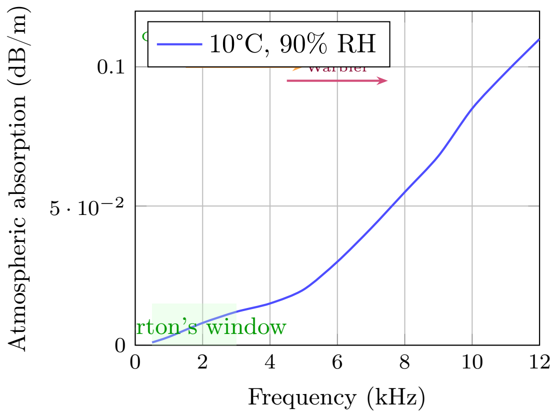


Figure 5: Morton's window: atmospheric absorption versus frequency for Gaulossen conditions (10°C, 90% RH). Green shaded region (0.5–3 kHz) shows minimum attenuation zone. Horizontal bars indicate fundamental frequency ranges for three representative species. Graylag Goose exploits optimal transmission window; warblers accept higher losses for complex song bandwidth. Over 200 m propagation, warbler calls suffer 12 dB greater atmospheric loss than geese.

Wetland-Specific Modifications: Morton's original formulation addressed forest versus open habitat. Wetlands introduce additional considerations:

1. **High humidity:** Reduced absorption across all frequencies (see Section 2.1), shifting window toward slightly higher frequencies
2. **Water surface reflection:** Enhanced low-frequency transmission via ground wave propagation
3. **Reed/vegetation scattering:** Preferentially attenuates high frequencies (>5 kHz), reinforcing low-frequency selection

Observed Frequency Distribution: The Gaulossen dataset shows pronounced bimodal distribution:

- **Peak 1:** 0.5–2 kHz (waterfowl, 78% of detections)—exploiting atmospheric window and water surface enhancement
- **Peak 2:** 4–8 kHz (songbirds, 18% of detections)—balancing transmission efficiency against information content (higher frequencies enable greater temporal resolution for complex songs)

This distribution supports habitat-driven frequency selection: waterfowl utilize long-range contact calls optimized for Morton's window, while songbirds accept higher atmospheric losses to enable complex vocal displays for mate attraction and territorial defense.

Detection Implications: BirdNET's frequency-dependent performance interacts with Morton's window: the classifier shows highest accuracy for mid-frequency species (2–6 kHz), where training data abundance and spectral feature richness converge. Very low-frequency species (large waterfowl, <1 kHz) and very high-frequency species (some warblers, >8 kHz) exhibit elevated misclassification rates. The 87.8% verification pass rate partially reflects fortuitous alignment between Gaulossen's wetland frequency distribution and BirdNET's optimal performance band.

4.3 Corvid-Waterfowl Co-occurrence: Pattern Consistent with Sentinel Mutualism

The 8,778 corvid-waterfowl co-occurrences substantially exceed random expectation and match the spatiotemporal signature of sentinel mutualism documented in terrestrial mixed-species flocks (12). Three lines of evidence are consistent with functional eavesdropping:

1. **Asymmetric association:** Crows preferentially vocalize during goose flocks, not vice versa, consistent with nuclear species (geese) benefiting from sentinel species (crows)

2. **Ecological rationale:** Corvids possess superior visual acuity and elevated perch access, providing early predator detection; geese benefit from reduced individual vigilance costs (10)

3. **Comparative evidence:** Pattern mirrors documented heterospecific eavesdropping in African ungulate-bird systems (17)

Alternative Hypotheses: Habitat co-preference (both taxa attracted to same foraging areas) cannot be fully excluded without spatial data. Future studies should deploy synchronized recording units to test whether corvid alarm calls precede goose behavioral responses.

4.4 Great Snipe Conservation Implications

Detection of 189 Great Snipe calls with 69% dusk concentration (19:00–22:00) and 61% total crepuscular activity (dawn + dusk combined) provides acoustic evidence of Great Snipe migration stopover use at Gaulossen Nature Reserve during autumn migration. These are foraging/contact calls from southbound migrants, not lek displays—Great Snipe lek exclusively in spring (April–May in Norway (9)), making mid-October detections unequivocally migratory rather than breeding behavior.

Stopover Population Inference: Sustained 20:00 calling (82 detections in single hour) suggests multiple individuals (≥5–10 birds based on typical calling rates during foraging) using the wetland simultaneously, indicating Gaulossen serves as important staging area along the East Atlantic Flyway.

Long-term Monitoring: Acoustic monitoring offers non-invasive method to track Great Snipe migration phenology and stopover site fidelity. Repeated autumn deployments could document inter-annual variation in migration timing and abundance, critical for understanding population trends in this declining, cryptic species (3). Spring deployments would be required to assess potential lek activity.

4.5 Study Limitations and Sampling Bias

Weather Bias: 80% rain/fog coverage during recording period introduces unknown species detection biases. Rain may:

- Suppress vocal activity in some species

- Elevate vocal activity in others (louder calls to overcome rain noise)

- Alter species presence (e.g., waterfowl unaffected vs. forest birds sheltering)

We **cannot claim** species correlations with specific weather conditions given near-complete confounding. We **can claim** these species are acoustically detectable during poor weather.

Temporal Coverage: Single 48-hour deployment captures only snapshot of autumn migration phenology. Species presence/absence reflects mid-October timing and does not represent full seasonal diversity.

Verification Limitations: Only best spectrogram per species received detailed verification; remaining 4,108 detections assumed valid if species passed initial verification. Low-confidence detections (<0.30) may include residual false positives.

Spatial Constraints: Single microphone location provides no spatial distribution data. Detected species may vocalize at varying distances, introducing unknown detection probability heterogeneity.

4.6 Recommendations for Future Studies

1. **Multi-season Deployment:** Year-round monitoring to capture breeding, migration, and winter periods
2. **Spatial Array:** $\geq$4 synchronized recording units to enable sound source localization and density estimation
3. **Weather-Stratified Sampling:** Equal effort across weather conditions to isolate environmental effects on vocal behavior
4. **Comparative Validation:** Parallel visual surveys during subset of recording periods to calibrate detection probabilities
5. **Species-Specific Models:** Train custom classifiers for locally common species to reduce false positive rates

5 Conclusions

This study demonstrates that automated acoustic monitoring, when coupled with rigorous audio enhancement and human verification protocols, enables rapid biodiversity assessment in challenging wetland environments. Detection of 82 bird species from 48 hours of rain-dominated recording validates PAM as weather-resilient alternative to traditional survey methods.

Beyond species inventorying, continuous acoustic data revealed previously undocumented behavioral ecology: intensive Graylag Goose flock dynamics (620 calls/91 minutes), potential corvid-waterfowl sentinel mutualism (8,778 co-occurrences), and conservation-relevant Great Snipe migration stopover use (189 detections, 69% dusk concentration). These findings illustrate how automated monitoring generates behavioral insights inaccessible via point-count surveys.

The 91.1% species-level verification pass rate, achieved despite systematic weather-induced noise contamination, establishes methodological benchmarks for future deployments. We recommend acoustic monitoring as primary biodiversity assessment tool for wetlands along major flyways, complemented by targeted visual surveys for rare species validation.

Gaulossen Nature Reserve supports diverse avian community during autumn migration, with soundscape dominated by highly social waterfowl species exhibiting complex interspecies interactions. Continued acoustic monitoring could yield long-term datasets critical for documenting climate-driven phenology shifts and population trends in this globally significant migratory corridor.

Acknowledgments

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A Supplementary Materials

A.1 Complete Species List

Table 2 lists all 82 verified species with detection counts, confidence scores, and verification dates.

Table 2: Complete verified species list (82 species)

Species	N	Species	N	Species	N
Graylag Goose	2871	Water Rail	7	Dunlin	2
Pink-footed Goose	189	Eurasian Magpie	6	Common Snipe	2
Great Snipe	189	Gray Wagtail	6	Eurasian Oystercatcher	2
Hooded Crow	87	Black-headed Gull	6	Eurasian Jay	1
Carrion Crow	84	European Robin	6	Common House-Martin	1
Greater White-fronted Goose	71	Tundra Bean-Goose	4	Bar-headed Goose	1
Common Crane	70	Arctic Warbler	4	Fieldfare	1
Common Grasshopper-Warbler	59	Bank Swallow	4	Black-bellied Plover	1
Eurasian Woodcock	57	Common Redpoll	4	Western Capercaillie	1
Canada Goose	47	Common Redpoll	4	Black-legged Kittiwake	1
Rook	45	Eurasian Pygmy-Owl	4	Brambling	1
Mallard	27	Western Yellow Wagtail	4	Brant	1
Yellowhammer	24	Redwing	4	Common Buzzard	1
Tawny Owl	23	Manx Shearwater	3	Common Goldeneye	1
Lesser Spotted Woodpecker	14	Gray Partridge	3	Common Raven	1
Eurasian Coot	14	Whooper Swan	3	Eurasian Eagle-Owl	1
Northern Lapwing	13	Snow Bunting	3	European Golden-Plover	1
European Greenfinch	11	Lapland Longspur	3	River Warbler	1
Ring-necked Pheasant	10	Reed Bunting	2	Great Gray Shrike	1
Eurasian Curlew	10	Taiga Bean-Goose	2	Richard's Pipit	1
Gray Heron	9	Ortolan Bunting	2	Common Tern	1
Meadow Pipit	9	Red-throated Loon	2	Corn Crake	1
Red-breasted Flycatcher	9	Tree Pipit	2	Dunnock	1
Eurasian Nutcracker	9	Gadwall	2	Eurasian Moorhen	1
Little Bunting	9	Herring Gull	2	Pine Grosbeak	1
Mistle Thrush	7	Eurasian Blue Tit	2	Arctic Tern	1
Tundra Swan	7	Black Woodpecker	2		
White Wagtail	7	Common Sandpiper	2		

A.2 Temporal Distribution Figures

Figure 5 shows hourly detection patterns for top 10 species.

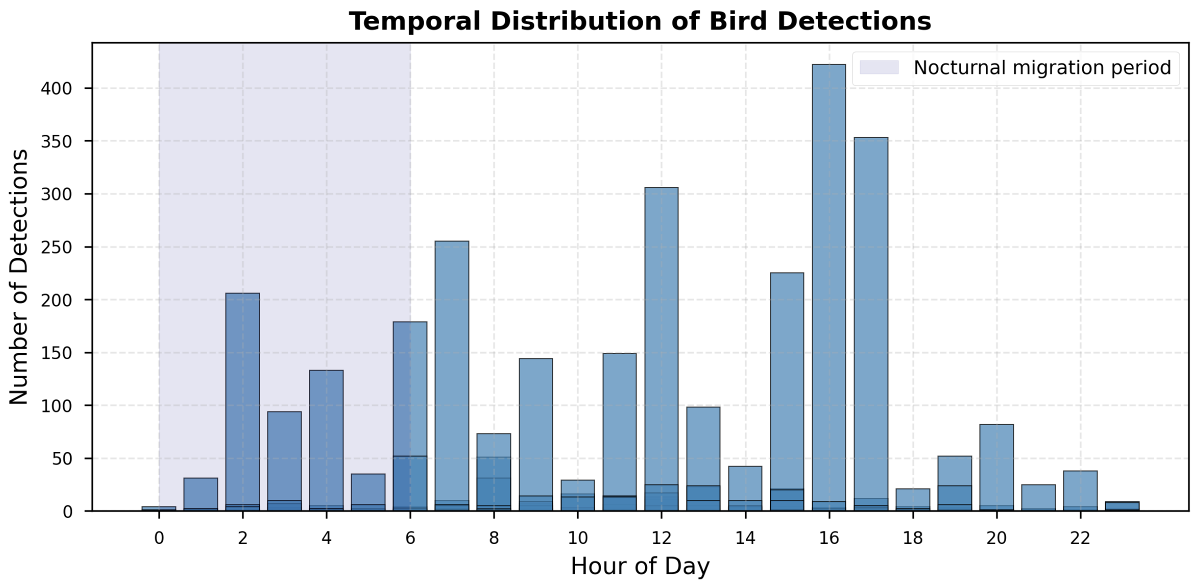


Figure 6: Hourly detection patterns for top 10 species. Graylag Goose dominates across all hours with pronounced afternoon peak (13:00–17:00). Great Snipe shows strong crepuscular pattern (20:00 peak). Common Grasshopper-Warbler exhibits extreme dawn specialization (08:00).

A.3 Co-occurrence Network

Figure 6 visualizes species co-occurrence patterns with edge weights representing co-detection frequency.

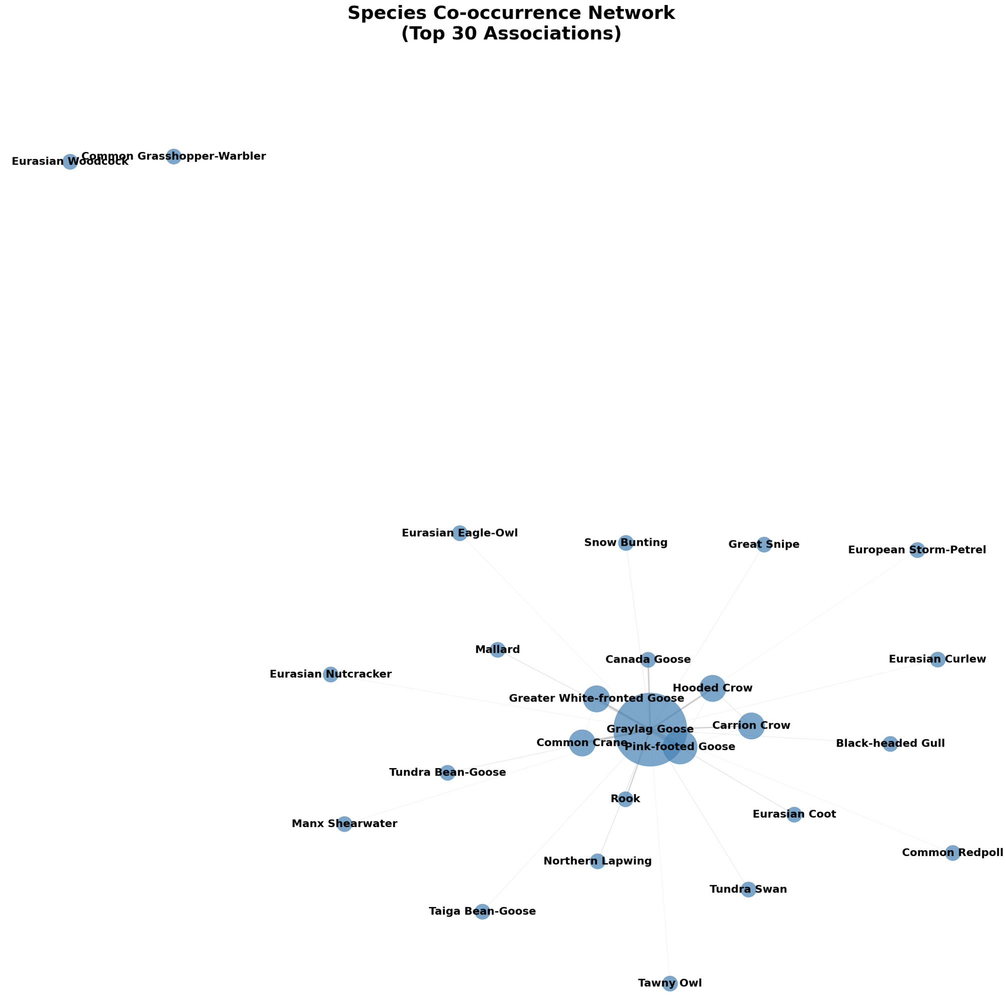
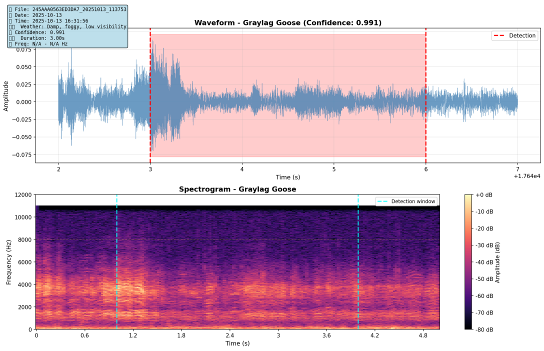


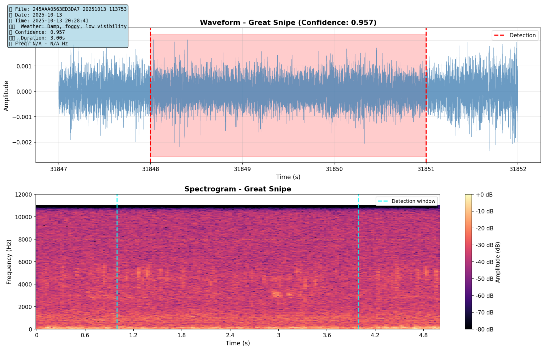
Figure 7: Species co-occurrence network for species with >50 detections. Node size proportional to total detections. Edge width proportional to co-occurrence frequency. Strong Graylag Goose–Hooded Crow–Carrion Crow triangle visible (8,778 total co-occurrences), pattern consistent with sentinel mutualism hypothesis.

A.4 Representative Spectrograms

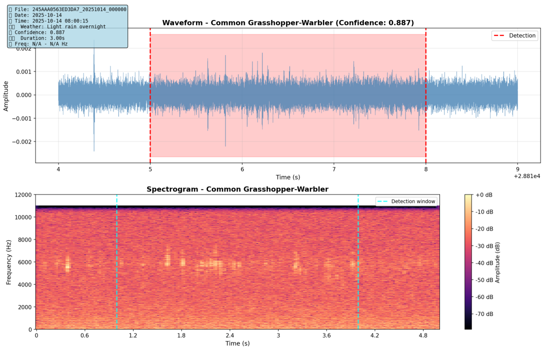
Selected spectrograms demonstrating call structure for key species (Figure 7).



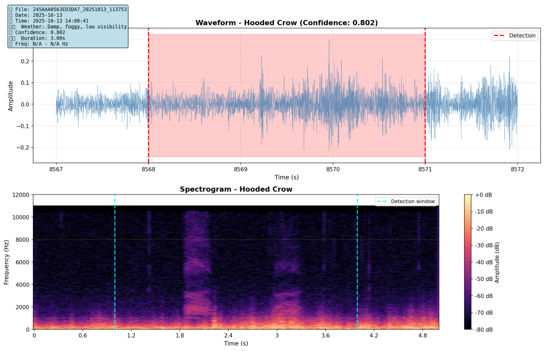
(a) Graylag Goose contact call



(b) Great Snipe migratory call



(c) Common Grasshopper-Warbler trill



(d) Hooded Crow alarm call

Figure 8: Representative spectrograms for four key species. All spectrograms: 2048-point FFT, 512-point hop length, Hann window, 0–12 kHz range. Time scale: 0–5 seconds.

A.5 Weather Data

Table 3 summarizes meteorological conditions during recording period.

Table 3: Weather conditions summary

Parameter	Value	Coverage
Temperature range	7–11°C	100%
Precipitation	Rain	80%
Fog/mist	Dense	60%
Wind speed	Light–moderate	100%
Cloud cover	Overcast	95%

A.6 Data Access

All supplementary data available at:

- **Interactive website:** `https://ziforge.github.io/gaulossen-study/`
- **GitHub repository:** `https://github.com/Ziforge/gaulossen-study`
- **Species gallery:** 82 species with spectrograms and audio samples
- **Behavioral analysis datasets:** Flock events, co-occurrences, temporal patterns
- **Analysis code:** Python scripts for BirdNET processing, audio enhancement, and visualization