TABMON: design and deployment of a transnational passive acoustic monitoring network for European birds

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Abstract:

1. Ecological surveys are often fragmented, costly, and limited in scale, leading to large and long-standing knowledge gaps which threaten our ability to properly safeguard biodiversity.

2. Passive Acoustic Monitoring (PAM) has promised to deliver automated biodiversity monitoring, but networks are rarely deployed on scales that can offer truly novel insights due to scalability and standardisation challenges around collecting, managing, analysing, and sharing data.

3. Here we present the Transnational Acoustic Biodiversity Monitoring Network (TABMON), a standardised deployment of 108 autonomous sensors across Norway, Netherlands, France and Spain along a continental bird migration route. Audio is recorded continuously, uploaded in near real-time, and processed through an automated analysis pipeline designed to support expert validation and the generation of datasets for deriving Essential Biodiversity Variables (EBVs).

4. TABMON provides a methodological blueprint for transnational, networked PAM deployments and highlights both the opportunities and current limitations of near-real-time acoustic biodiversity monitoring at continental scales.

1. Introduction

Obtaining reliable biodiversity data across large spatial and temporal scales remains a major challenge (Kissling et al. 2026). Despite decades of research documenting substantial biodiversity knowledge gaps (Faith et al. 2013; Santana et al. 2025), these deficiencies persist due to the high financial and logistical demands of traditional field surveys, the need for specialised taxonomic expertise, and the fragmented nature of existing monitoring efforts (Wetzel et al. 2018). Across Europe, biodiversity observation continues to suffer from pronounced taxonomic, spatial, and temporal biases (Santana et al. 2025; Darras et al. 2025), with many habitats and species groups poorly represented and national programmes operating with limited coordination (Moersberger et al. 2024). Such heterogeneity in methods and coverage impedes the operationalisation of Essential Biodiversity Variables (EBVs) and constrains the integration of biodiversity information across borders and biogeographical regions (Lumbierres et al. 2025). Addressing these challenges requires the establishment of scalable and standardised observation frameworks capable of delivering reliable biodiversity data at continental scales (Kissling et al. 2026). Recent advances in digital sensing technologies and autonomous monitoring approaches (Besson et al. 2022) offer a promising path forward by enabling cost-effective, high-frequency, and spatially distributed biodiversity data streams that can bridge existing monitoring gaps and strengthen Europe's capacity for coordinated biodiversity assessment.

Among emerging technologies for large-scale biodiversity observations, passive acoustic monitoring (PAM) has become a leading approach owing to its ability to detect multiple taxa simultaneously, its low sensor cost, and the growing capabilities of automated processing pipelines (Gibb et al. 2019). Although numerous PAM studies have generated valuable insights at local or short-term scales (Darras et al. 2025; Ross et al. 2023; Sugai et al. 2019), applications delivering consistent data across large spatial or temporal extents remain rare. Key barriers include equipment and maintenance costs, data management complexity, and slow uptake of standardised protocols (Sugai et al. 2019).

Most PAM deployments rely on recording devices that store data locally, requiring periodic site visits for battery replacement and manual retrieval of storage media (Hill et al. 2019). These constraints often result in fragmented temporal coverage, delayed data access, and limited opportunities for timely quality control. In large or remote study areas, logistical constraints can further lead to extended gaps in data collection and reduced continuity of long-term monitoring efforts. In parallel, distributed citizen-science projects have helped cost-effectively expand spatial coverage to scales not achievable by small dedicated field teams (Newson et al., 2015; Roe et al., 2021). However, data quality is impacted by variable sampling effort and observer expertise, and continued coordination of citizen scientists can be complex, time consuming, and costly. Networked autonomous recorders powered by off-grid energy sources (e.g. solar) address several of these limitations by enabling continuous operation, automated data transmission, and near real-time monitoring of device status and data availability (Sethi et al., 2018, 2021). This approach reduces delays between data collection and analysis, supports early detection of device failure, and facilitates standardised workflows across geographically distributed sites. Coupled with automated

85 species identification algorithms, such systems enable rapid, standardised, and high-
86 throughput analysis of large acoustic datasets (Bick et al., 2024; Sethi et al., 2020). Although
87 requiring higher initial investment, they support long-term, low-maintenance deployments,
88 near real-time quality control, and streamlined data integration. Together, these innovations
89 position PAM as a practical foundation for standardised, continuous, and continent-scale
90 biodiversity monitoring.

91 Here, we describe the design, deployment and operational workflow of TABMON; a
92 Transnational Acoustic Biodiversity MOnitoring Network. Deployed across four European
93 countries along a large latitudinal gradient (108 sites spanning a latitudinal gradient of 3,649
94 km) targeting terrestrial bird species, TABMON aims to: (i) push scalability limits by
95 deploying the first standardised PAM network across multiple European countries and
96 biomes, (ii) deliver tailored machine learning workflows for acoustic identification of
97 European birds at a transnational scale, and (iii) fill spatiotemporal and taxonomic gaps in
98 our understanding of the breeding behaviour and migration timing of terrestrial birds across
99 Western Europe (Flack et al. 2022).

2. Sampling design

101 The TABMON network spans Norway, the Netherlands, France and Spain, covering a
102 latitudinal gradient of 3,649 km (Varanger in Finnmark, Norway to Delta del Ebre in
103 Catalonia, Spain) and a longitudinal gradient of 3,539 km (Pasvik in Finnmark, Norway to
104 Mas de Melons in Catalonia, Spain). The network encompasses representative landscapes
105 along major terrestrial bird migration routes in Western Europe and includes habitats of
106 importance to both diurnal and nocturnal species. In total, we selected 108 sites (51 in
107 Norway, 18 in the Netherlands, 21 in France and 18 in Spain; Figure 1), where autonomous
108 acoustic sensors were deployed between January and April 2025 and will remain operational
109 until at least January 2027, covering two complete annual migration cycles. For each
110 deployment, field teams recorded key metadata including GPS coordinates (longitude,
111 latitude), deployment date (YYYY-MM-DD HH:MM-SS format), microphone height (cm) and
112 microphone directionality (cardinal direction or degrees), together with a short field
113 description of the site (e.g. habitat context or connectivity issues). Photographs of the device
114 and surrounding environment (e.g. front, back, left, right) were also collected to support later
115 interpretation of the recordings and troubleshooting of technical issues. The complete
116 deployment metadata are provided in Table S1.1 in Supplementary Material S1, and the
117 deployment form used in TABMON to collect site metadata is included in Supplementary
118 Material S2.

119 Site selection followed a combination of ecological relevance and logistical feasibility.
120 Ecologically, sites were prioritised along known or suspected migration flyways and in
121 habitats frequently used as breeding areas, migration corridors or stopover sites. Selection
122 was informed by local ornithological expertise and existing knowledge of bird hotspots.
123 Several deployments were co-located with established monitoring efforts, such as long-term
124 breeding bird surveys, point counts, ringing stations or citizen science observation networks,
125 enabling cross-validation and integration of acoustic detections with conventional monitoring
126 data. In addition, some locations were selected to improve monitoring of nocturnal and
127 cryptic species, which are typically underrepresented in traditional surveys. A complete

128 description of our site selection protocol can be found in Supplementary material S3.
129 Logistical criteria included accessibility (sites reachable within approximately one hour on
130 foot or skis), cellular network coverage (4G/5G connectivity for data transmission), and
131 proximity to partner institutions or trusted local contacts able to intervene in case of
132 equipment failure (generally within 100 km). The uneven distribution of sites among
133 countries reflects differences in logistical constraints, partner capacity, and opportunities for
134 off-grid deployments rather than a stratified sampling design across environmental,
135 anthropogenic and policy gradients (Kissling et al. 2026). Although such geographic
136 imbalance may introduce bias if not considered during analysis, appropriate statistical
137 approaches such as stratified sampling or model-based sampling can mitigate these effects
138 (McEwen et al. 2025).

139 Sites, defined by the GPS coordinates where individual sensors were deployed, were
140 grouped into clusters of two to six devices. Each cluster represents a geographical unit such
141 as an island, peninsula, or protected area containing suitable habitats for migrant passerines
142 or nocturnal birds, as identified by local ornithologists. The cluster design improves logistical
143 efficiency for installation and maintenance while increasing data robustness, as recordings
144 from multiple devices within a cluster can partially compensate for temporary device failures.
145 Within clusters, the median distance between devices is 3.71 km, ranging from 278 meters
146 (Utsira) to 54 km (Trondelag) (Figure S1.1 and Table S1.2 in Supplementary Material S1). At
147 local scales, devices are typically separated by >250 m, which reduces the likelihood of the
148 same bird vocalisation being recorded by multiple devices (Metcalf et al. 2023). Larger
149 distances within cluster distances mainly occur in extensive protected areas or remote
150 landscapes, such as northern Norway, where suitable deployment locations are widely
151 spaced. In more human-dominated landscapes, where suitable habitats are smaller and
152 more fragmented, clusters tend to be more compact, as observed in the Netherlands and
153 France.

TABMON clusters
Circle colour represents number of devices
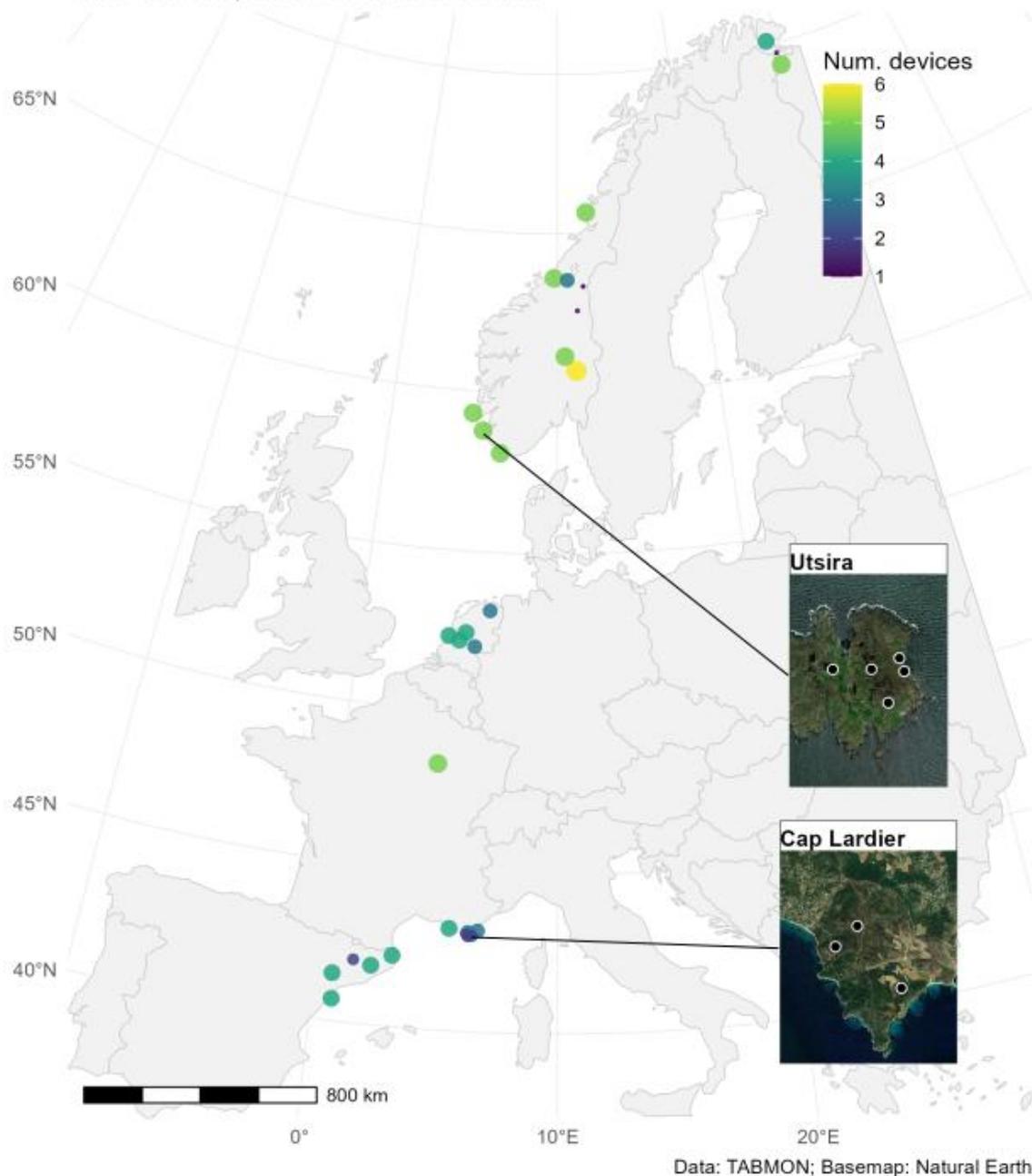
Figure 1. Locations of the TABMON clusters spanning Norway, Netherlands, France, and Spain with circle color representing the number of devices within clusters. Small dark blue circles represent single devices. Inset maps represent a detailed view of the Utsira and Cap Lardier clusters.

3. Sensors and off-grid power

161 At each site, we deployed a Bugg device (Sethi et al. 2018) which transmits near real-time,
162 compressed audio data over a 4G/5G mobile internet connection. Each unit records 5-
163 minute monochannel audio files continuously (24 h per day) at a sampling rate of 44.1 kHz
164 to capture the full range of audible bird vocalizations. MP3 variable bit rate (VBR0)
165 compression is required as most mobile networks do not have sufficient bandwidth to
166 support continuous uncompressed audio transmissions.

167 Each Bugg is powered by an external lithium battery charged by a solar panel, enabling
168 continuous recording when local conditions allowed (Figure 2). For instance, daylight and
169 temperature limited autonomous operation in Norway to roughly mid-February through mid-
170 October, whilst devices in Spain record year-round. Power-system specifications differed
171 between countries according to site accessibility, resource availability, and local equipment
172 availability (Tables S4.1, S4.2, S4.3 and S4.4 in Supplementary Material S4).

173 To limit setup-related bias, consistency in device deployments across all sites is prioritised.
174 Where possible, devices are deployed at a height of between 1 and 2 m (using trees or
175 poles) (Metcalf et al. 2023). However, in some cases, devices are placed higher (i.e. up to
176 4.5 m, to limit vandalism and theft risks, damages from grazing animals, snow or vegetation
177 coverage) or lower (i.e. minimum 0.9 m, to limit wind exposure). Bugg devices are primarily
178 oriented with microphones facing towards the habitat of interest. When strong winds could
179 interfere with the recording (e.g. coastal scrublands), the orientation is adjusted to reduce
180 exposure (i.e. opposite to prevailing wind direction). In dense habitats with limited sunlight
181 (e.g. forests), devices are typically installed along south-facing edges or in clearings,
182 directed toward the target habitat. On sloped terrain or where obstacles restricted
183 deployment, the Buggs were positioned towards the most open area. Devices are mounted
184 in an upright position whenever possible, with a slight upward or downward tilt when installed
185 at a non-standard height or when placed on a slope.
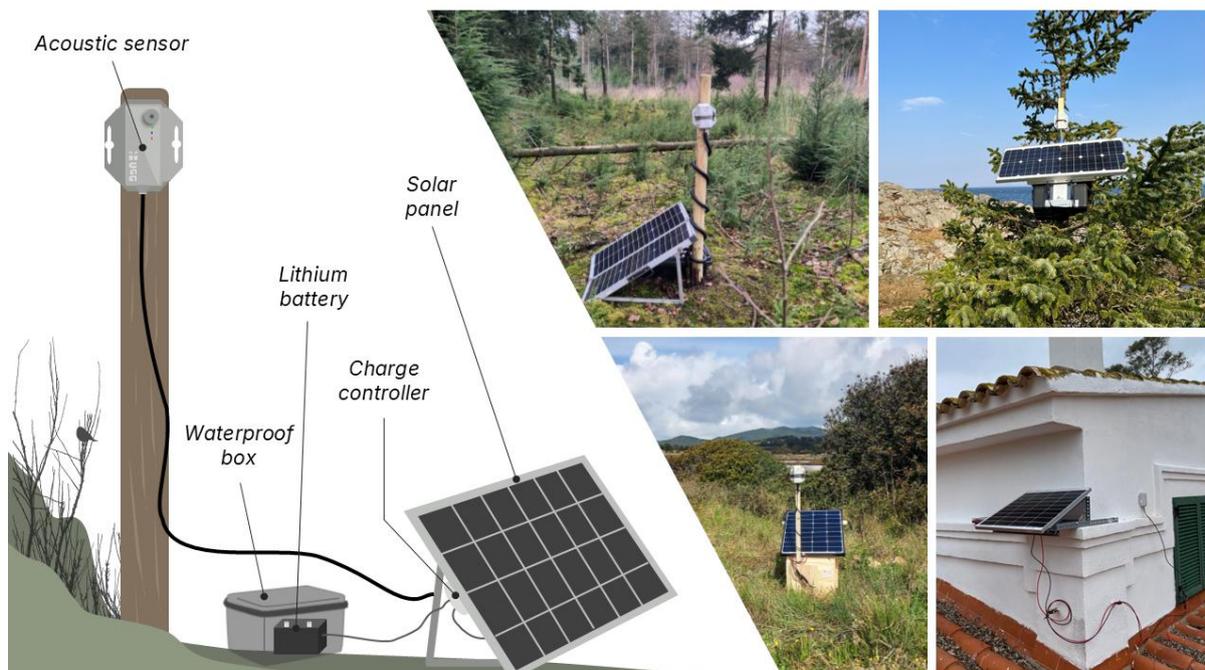
186 **Figure 2.** Schematic view of the Bugg acoustic sensor deployment set up (left-hand side)
187 and example deployment pictures (right-hand side).

188 ## 4. Data ingestion pipeline and server architecture

189 ### *4.1. Infrastructure and servers*

190 Immediately after recording, files are uploaded to Google Cloud, where they are
191 automatically transferred once per day onto a storage bucket hosted by the Norwegian
192 Infrastructure for Research Data (NIRD: NIRD — Sigma2 documentation) to reduce costs of
193 data storage (Figure 3). Given its flexibility in access policy, the NIRD bucket serves as the
194 primary entry point for the consortium, providing partners with direct access to the recordings
195 as well as the metadata. The NIRD bucket is mounted as S3-compatible storage, which
196 allows both (i) our TABMON dashboard to visualize network status and data availability, (ii)
197 our TABMON Listening Lab to serve users with BirdNET detection clips for annotation and
198 (iii) partners to directly access raw recordings for quality checks or independent analysis.

199 For long-term stability and computationally intensive tasks, the entire dataset is copied once
200 per month to a dedicated server at the University of Toulon's Laboratoire d'Informatique et
201 des Systèmes server (LIS server), where access is more restricted than on the NIRD bucket.
202 This LIS server acts as the archival repository for TABMON and hosts most of the large-
203 scale analysis (Figure 4). The LIS server is equipped with 40 NVIDIA GPUs (primarily A100,
204 A40, and RTX 3090) and 250 TB of storage dedicated to the project. Under this
205 configuration, processing a 5-minute file takes an average of 8 seconds. Analyses are
206 performed on a monthly basis, using up to ten jobs in parallel.
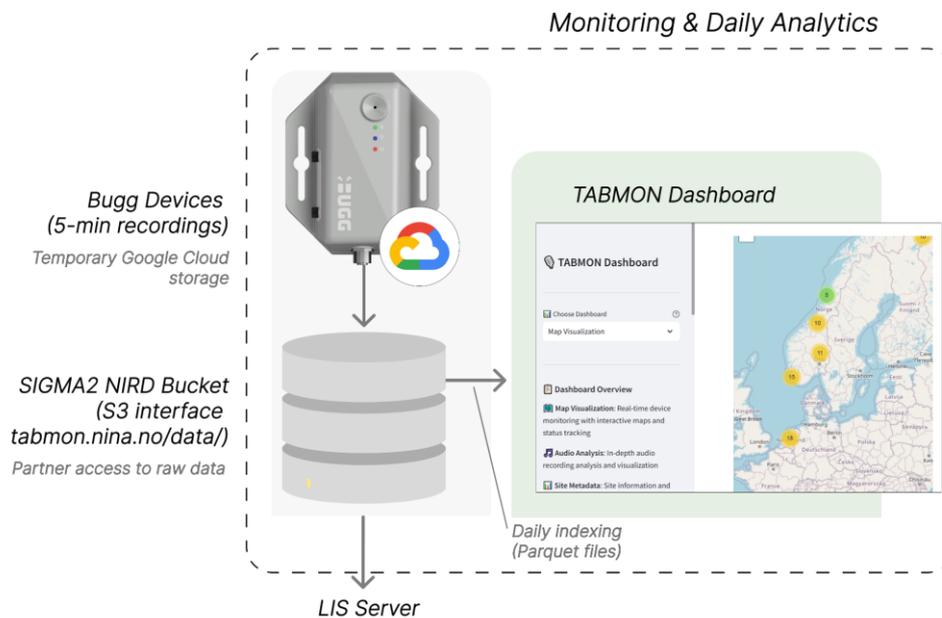
207

208 **Figure 3.** TABMON data collection and infrastructure. Audio is uploaded in near real-time
209 from Bugg devices in the field to a Google Cloud Storage bucket. Data is then transferred to
210 a Norwegian Infrastructure for Research Data (NIRD) server, where it can be accessed by

211 partners and visualised through a dashboard. Data is copied to the University of Toulon's
212 LIS server for long-term archival storage and analysis.

213 *4.2. Acoustic analysis*

214 Given the very large volume of audio produced by continuous recording (approximatively 25
215 TB of raw acoustic data in 2025 only), we employ an automated analysis pipeline. The
216 pipeline uses the BirdNET model (Kahl et al. 2021), which is able to identify over 6500 bird
217 species based on their vocalizations and has proven useful for European bird monitoring,
218 for instance for estimating community-level patterns in European soundscapes (Funosas et
219 al. 2024, 2026; Winiarska et al. 2025). We use BirdNET in TABMON as a screening tool for
220 extracting species-level predictions from continuous recordings.

221 We divide Each 5-minute recording into non-overlapping 3-second segments and process
222 them with BirdNET. For each segment, the model outputs a predicted species label and an
223 associated confidence score ranging from 0.01 to 1. This score indicates how strongly the
224 model supports a given species identification relative to other possible species in its
225 reference set (Wood and Kahl 2024).

226 We use BirdNET (v2.4) via the [TABMON data pipeline](#), built upon the [AvesEcho](#) service
227 (Ghani et al. 2024), and optimize the pipeline for parallel execution across multiple GPUs.
228 The AvesEcho filter takes the longitude and latitude of the recorder, the coordinates are
229 converted to a Military Grid Reference System (MGRS) coordinate extracting both time zone
230 and latitudinal band. This rectangle is used to clip the European Breeding Bird Atlas 2
231 [(EBBA2) occurrence map](#) (Keller et al. 2021) (i.e. where species have been reported to
232 breed) which is used to filter BirdNET predictions. Due to the focus on migratory species with
233 differing occurrence and breeding locations, this geographical filtering method was adjusted
234 to include a fixed set of MGRS coordinates (29W - 36S). This provides complete coverage of
235 TABMON sites and filters the BirdNet classes from 6522 to 480 species.

236 We store predictions and metadata in a database composed of Parquet files, enabling
237 efficient compression and fast column access. DuckDB enables SQL-based querying of
238 these files, and a FastAPI interface provides access to the data. In addition, we save the
239 three second clips for which the detection has been made for validation purposes. The data
240 pipeline and export interface are open-source and available on [GitHub](#).

241

242 *4.3. Data collection for BirdNET validation*
243
244 Automated predictions alone are often unreliable for ecological interpretation without
245 quantifying model accuracy under network-specific conditions (Tseng et al. 2025). BirdNET
246 performance may vary across species, habitats, seasons, devices, and background noise
247 regimes (Citovsky et al. 2021; Gregory and Strien 2010; Lehikoinen et al. 2019; Settles
248 2009), and these sources of variation must be assessed before deriving ecological indicators
249 such as species richness.
250

To validate BirdNET detections we use two complementary annotation platforms. The TABMON Listening Lab for Experts (https://tabmon-listening-lab-expert.nina.no/) is designed for trained ornithologists, with specific datasets being uploaded to this application following a strict protocol. For selected target species and sites, clips are sampled systematically across predefined BirdNET confidence-score intervals (0.1–0.2, 0.2–0.3, etc.), with a fixed number of clips drawn from each bin. This stratified sampling ensures that validation covers the full range of model confidence scores, rather than focusing only on high-confidence predictions (Tseng et al. 2025). Experts log in the application and review the audio segment where the detection has been made together with the BirdNET predictions and the clip metadata, and then confirm, correct or reject the suggested species labels.

In addition, trained volunteers and citizen scientists are able to review TABMON detections using the public facing TABMON Listening Lab (https://tabmon-listening-lab.nina.no/). The user is able to select a site or species of interest and confirm, correct or reject the BirdNET prediction. While expert annotations provide the basis for formal performance assessment (Figure 4a), citizen-science contributions increase annotation capacity and help broaden taxonomic and geographic coverage.

4.4 Data collection for BirdNET model refinement

In addition to validation, labelled clips are curated to support future model refinement for European acoustic conditions (Figure 4b). Species predictions in large-scale monitoring follow a long-tailed distribution, with common species dominating outputs and many taxa underrepresented, leading to underwhelming model performance for the infrequent species (Zhang et al. 2024). A naïve sampling approach would therefore provide limited information for improving model performance on rarer or acoustically challenging species. Acoustic recordings collected across countries, habitats, and devices are also subject to domain shifts, where background noise, habitat structure, seasonal soundscapes, and sensor characteristics differ from the conditions represented in model training data. Recent methodological work carried out as part of TABMON shows that structured sampling strategies accounting for class imbalance and spatiotemporal variation can substantially increase the value of person-time spent on annotation, for model adaptation (Bernard et al. 2025; McEwen et al. 2025).

In TABMON, annotation batches intended for model refinement are constructed using stratified sampling rather than simple random selection. Specifically, we construct batches using (i) a BirdNET confidence threshold lower-bound of 0.2 to reduce the false positive rate; combined with (ii) random selection with stratification across predicted species. The batches are sent to a trained ornithologists who confirm or infirm the detection through the TABMON Listening Lab. These annotated samples are finally used to fine-tune BirdNET's classification head (Multi-Layer Perceptron; MLP), i.e. to adapt the final part of BirdNET so it becomes better at identifying the bird species we are interested in. This protocol is informed by our previous work on efficient selection of samples (Bernard et al. 2025; McEwen et al. 2025). To date 2,000 samples have been annotated using this methodology (Cretois et al. 2025). Future work will investigate complementary strategies, including spatial and temporal

294   stratification, stratification by confidence bins, and uncertainty sampling (McEwen et al.
295   2025).

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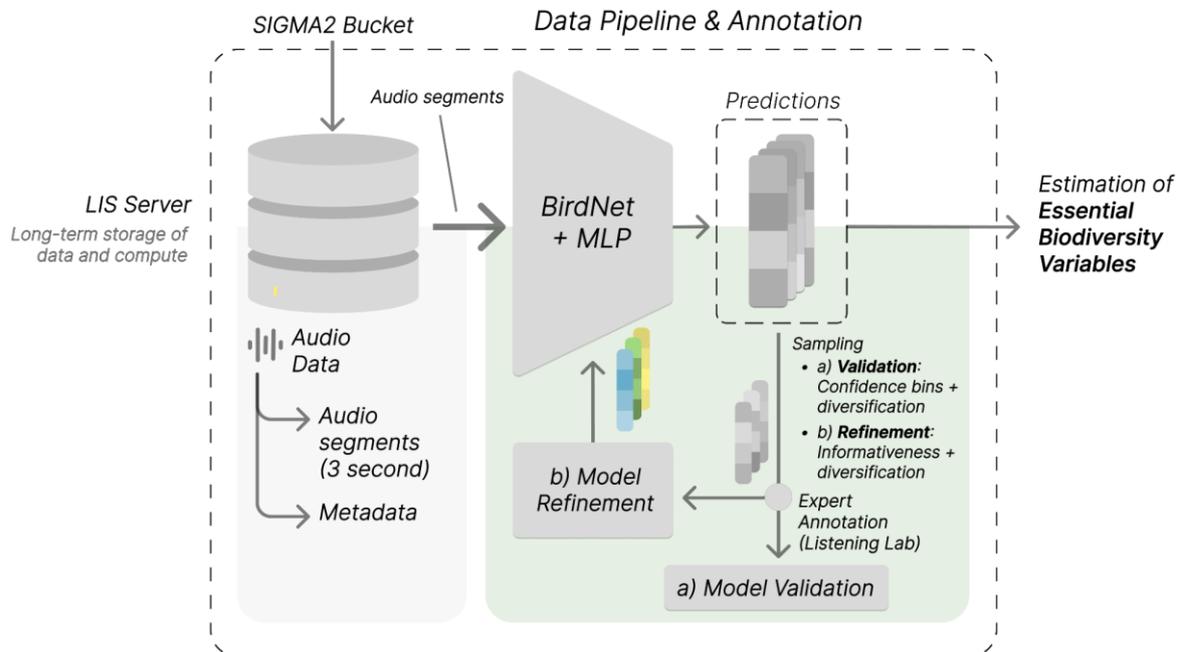
297
298   **Figure 4.** The TABMON data ingestion and analysis pipeline. Model predictions are
299   computed on a server which then inform sampling and expert annotation for model
300   performance validation and model training.

5. TABMON dashboard: accessing network status and metadata

302   The publicly accessible TABMON dashboard (https://tabmon.nina.no) provides a secure and
303   user-friendly interface for exploring the network's deployment, operational status, and
304   accumulated data. Built in Streamlit and deployed through Docker containers, the dashboard
305   interfaces directly with the NIRD S3 bucket. To keep the dashboard synchronized with
306   ongoing recordings, all files stored on NIRD are indexed daily. This process extracts files
307   metadata (i.e. device ID, country, site, file size) and writes it to a consolidated parquet file.

308   The interface is designed to serve both technical partners and the broader research
309   community. An interactive map presents the geographic distribution of the 108 Bugg sensors
310   deployed across the four countries, with device-level indicators showing operational status
311   and cumulative data volumes. For each sampling site, users can access a dedicated panel
312   displaying site metadata, including photographs, deployment details, and habitat information,
313   alongside summaries of recording effort and storage volumes (Figure 5).

314   By consolidating these features, the dashboard provides transparency on network
315   performance and facilitates collaboration among consortium partners. It represents the main
316   entry point to the TABMON infrastructure, allowing the consortium to monitor sensor uptime
317   and track accumulation of audio data.

318
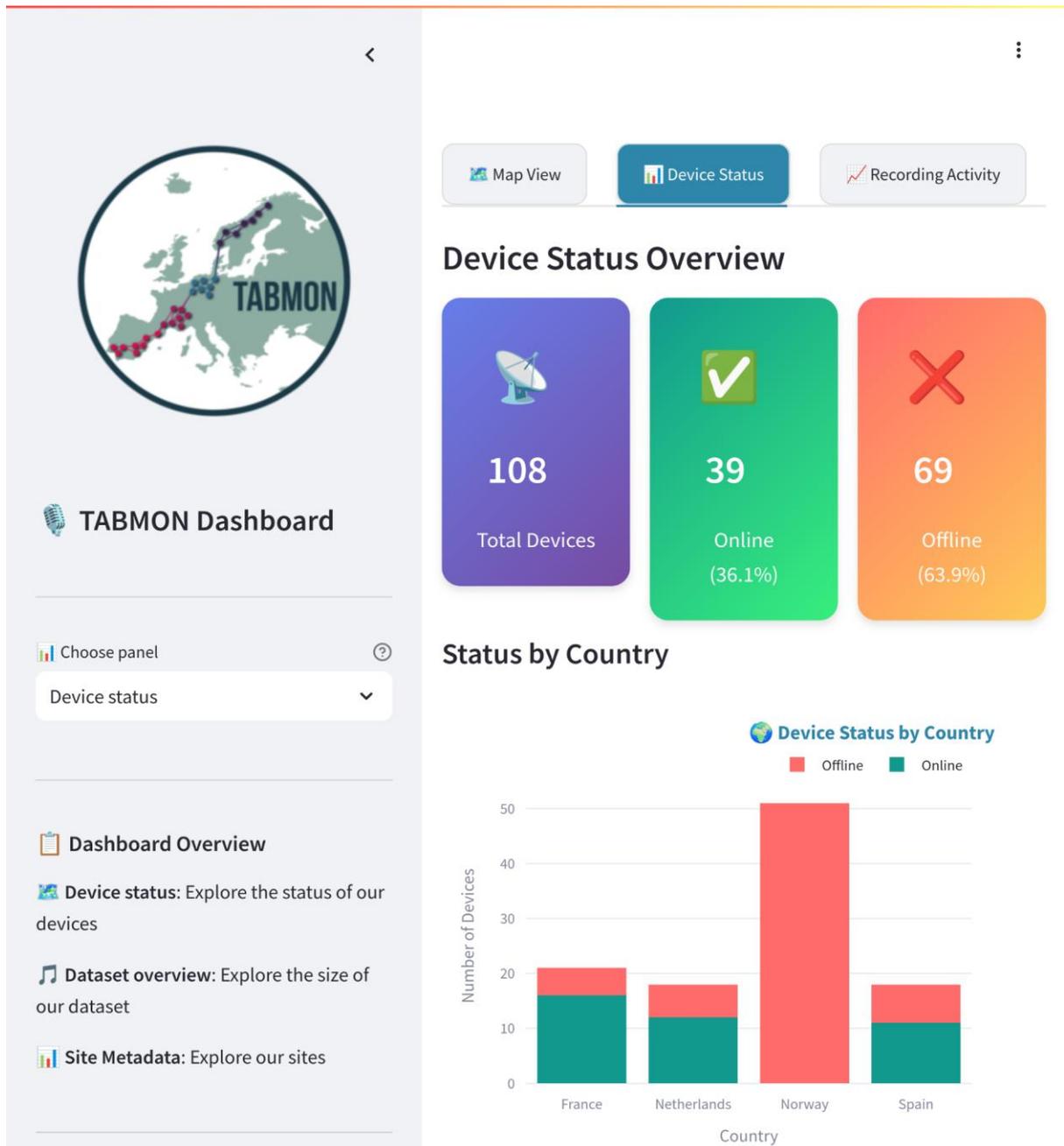
Figure 5. Screenshot of the dashboard User Interface. The user can select between three panels: Map Visualization to get a description of site location and online status as well as an overview of the existing dataset, Site Metadata to display the specific sites information including microphone heights and pictures and Audio Analysis which displays information related to the amount of data collected at a specific site.

6. Data sharing and downstream ecological insights

The primary goal of TABMON is to demonstrate how PAM can increase the extent and resolution of monitoring data and enable automated, cost-effective monitoring of terrestrial avian biodiversity. Birds are taxonomically well studied, responsive to environmental change and some species are highly vocal, making them ideal sentinels for biodiversity monitoring

329 (Gregory and Strien 2010). TABMON focuses on terrestrial avian occurrence and phenology,
330 with a particular emphasis on cryptic or night-active species which are vocally active but are
331 difficult to monitor with conventional schemes (e.g. owls, rails) (Duchac et al. 2020), and on
332 vocal migratory species whose behaviour and phenological timing are still relatively poorly
333 understood (Flack et al. 2022). TABMON is designed to support downstream ecological
334 analyses by providing standardised and reliable acoustic observations across diverse sites
335 from several European countries. The data produced in TABMON can thereby contribute to
336 workflows that generate Essential Biodiversity Variables (EBVs) for studying, reporting and
337 managing biodiversity change (Boyd et al. 2023; Kissling et al. 2018; Lumbierres et al.
338 2025). Specifically, the currently produced TABMON data can be seen as 'EBV-useable data
339 sets' (Kissling et al. 2018) in which raw observations (i.e. sensor detections with AI-inferred
340 species identities and confidence scores) are assembled together with accessible metadata
341 (e.g. timestamp, deployment information, audio filenames, data-sharing licenses). This
342 includes having time formats, spatial information and species identities in a standardized
343 way and to openly share these data for subsequent processing (Wiel et al., 2026).

344 In a second step, TABMON is also working on providing 'EBV-ready datasets' (Kissling et al.
345 2018). This requires further data quality and cleaning checks, i.e. assessing the accuracy of
346 AI detections and identifying errors and wrong identifications. In this context, comprehensive
347 validations of BirdNET confidence scores across species and sites are needed, including
348 assessments of universal and species-specific thresholds (Funosas et al. 2024, 2026; Tseng
349 et al. 2025). TABMON facilitates this by providing online interfaces for validation through
350 expert or citizen scientists (for instance through the TABMON Listening Lab). The validated
351 data can then be used to increase the precision of the acoustic detections generated by
352 automated classifiers (i.e., the percentage of true positives out of all the identified
353 predictions). For example, validated detections can be transformed into calibration curves
354 with a certain threshold of precision (e.g. 0.9 or 0.95) to provide reliable species occurrences
355 that can be summarised into presence or detection frequency within defined spatial (site,
356 cluster, region) and temporal (daily, seasonal, annual) units. Similarly, temporal patterns in
357 vocal activity can then be reliably aggregated to derive phenology-related variables, such as
358 the timing of arrival, peak vocal activity, or breeding-related calling periods, and compared to
359 citizen science, e.g. from EuroBirdPortal (Border et al. 2024; Bota et al. 2020).

360 While raw audio recordings cannot be made publicly available due to data privacy
361 considerations and because of logistical constraints (e.g. no online repository accept such
362 amount of data at the moment), TABMON is committed to sharing derived products (e.g.
363 EBV-useable and EBV-ready datasets), including metadata, automated predictions, and
364 expert annotations. By making these standardised observation-level outputs openly
365 available, TABMON supports reproducibility, independent evaluation, and reuse in EBV-
366 oriented analyses and broader biodiversity monitoring initiatives. All bird detections produced
367 as part of the TABMON project (EBV-useable datasets) and the expert annotations can be
368 found on Zenodo and will be updated with the latest analysis (Cretois et al. 2025).

369 We recognise that the absence of publicly accessible raw audio limits certain forms of
370 reproducibility, independent method benchmarking, and re-analysis using alternative
371 detection algorithms. However, we believe that sharing the expert annotations along with the
372 audio clips will contribute to the global effort to better benchmark and refine new methods

373 and models. This represents a trade-off between open data principles, logistical and legal
374 and ethical constraints associated with continuous environmental audio recording.

375

7. Key costs of the TABMON sensor network

377 One of the largest barriers to wider uptake of autonomous monitoring is the significant cost
378 of deploying and maintaining sensor networks (Speaker et al. 2022). Whilst a full economic
379 analysis is beyond the scope of this paper, here we outline a few key considerations and
380 trade-offs (Table 1).

381 The unique choice to use networked sensors affects TABMON's costs in several ways.
382 Compared to non-networked sensors, connected devices are more expensive (e.g., ~€1000
383 per Bugg vs ~€130 per AudioMoth) and require SIM cards with monthly network costs
384 (€1.89-12.52 for 40GB+ monthly). Additionally, each device is connected to its own off-grid
385 solar power system incurring a one-off cost of €300-400. However, the chosen sensor and
386 power delivery systems significantly reduce the operational workload and costs associated
387 with battery replacement, SD card collection, and device maintenance visits, an essential
388 consideration for TABMON given the wide geographic distribution of sites and the difficulty of
389 accessing many locations.

390 Beyond our choice for automated data submission, there are also the usual costs of
391 collecting, managing, and analysing large datasets. The network of 108 sensors can upload
392 over 110GB of audio daily, all of which incurs both networking costs (i.e. egress fees, as
393 data is moved between servers or cloud providers) and storage costs. As a reference, we
394 pay ~€200 monthly to transfer 2TB of data from Google Cloud to our NIRD bucket and €100
395 / TB / year for data storage on NIRD. In total, the average cost of the network is €1350 per
396 Bugg for deployment, plus €150 per Bugg per year for data transfer and storage.
397 Additionally, computational costs accumulate depending on the complexity of analyses used.
398 Much of our pipeline is hosted in subsidised research infrastructure, but commercial cloud
399 offerings would be more expensive. Finally, when skilled volunteers are not available,
400 ornithologists must be paid to annotate BirdNET predictions to ensure that TABMON delivers
401 reliable biodiversity insights throughout its deployment (approximately 1€ per three-second
402 annotations).

403 The sensor network also carries an environmental cost. The production of the sensor and its
404 power supply system is estimated to result in a carbon footprint of 383 kg CO_2e per Bugg,
405 while data transfer, storage, and processing contribute an additional 37 kg CO_2e per Bugg
406 per year (See Table S5.1 and Table S5.2 in Supplementary Material S5).

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408

409

Table 1: Indicative costs for deployment, operation, and analysis in the TABMON project

Cost category	Item	Unit cost (€)	Frequency	Notes
Hardware (one-off)	Bugg acoustic sensor	~ 1,000	Per device	Networked, autonomous recorder
Hardware (one-off)	Solar power system (panel + battery)	300-400	Per device	Enables off-grid operation
Deployment (one-off)	Installation and setup	Site-dependent	Per site	Travel and labour costs vary by location
Data transmission (recurring)	SIM card & mobile data	1.89-12.52 / month	Per device	Depends on national provider and data volume
Data storage (recurring)	Cloud egress (Google -> NIRD)	~ 200 / month	Network-wide	Approx. 2 TB transferred per month
Data storage (recurring)	Long-term storage (NIRD)	~ 100 / TB / year	Network-wide	Scales with accumulated data volume
Computation	Analysis infrastructure	Subsidised	Every month	Hosted on national research infrastructure
Annotation	Expert annotation	~ 1 / 3-second clip	As required	Depends on availability of skilled annotators

8. Discussion

TABMON demonstrates that transnational acoustic data collection and centralised processing are technically feasible at continental scales. By deploying a harmonized network of 108 autonomous recorders from the Arctic to the Mediterranean, we provide the first working example of a transnational PAM system that continuously generates avian biodiversity data across multiple European biomes. This approach moves acoustic monitoring beyond small-scale or short-term applications, illustrating how digital sensing, automated analysis, and shared data infrastructures can together deliver scalable, high-resolution biodiversity observations.

8.1. Integrating acoustics into continental biodiversity monitoring

TABMON establishes a methodological template for harmonizing autonomous acoustic monitoring across borders. The combination of standardized deployment protocols, centralized data ingestion, and open-source analytical pipelines enables reproducible, comparable, and rapidly accessible biodiversity information. These characteristics address long-standing issues of fragmentation among national monitoring programmes (Moersberger et al. 2024b), help to operationalize EBV workflows at a European scale (Kissling et al. 2026; Lumbierres et al. 2025), and support global biodiversity reporting frameworks based on regional observation systems (Gonzalez et al. 2023). The integration of near real-time data

430 transmission with cloud-based processing further facilitates quality control and adaptive
431 sampling, opening the door to "digital observatories" for biodiversity.

8.2. Methodological lessons and challenges at scale

433 Operating at continental scale exposed substantial logistical and technical challenges, from
434 limited daylight and freezing temperatures constraining solar-powered devices in northern
435 regions to connectivity and equipment interference challenges in more populated southern
436 areas. These contrasts highlight the need for a flexible monitoring architecture that combines
437 networked, solar-powered sensors in remote sites with lower-cost, periodically serviced units
438 where access is easier. While near real-time connectivity reduces maintenance effort, it also
439 increases the cost of power and data transmission (Kissling, Evans, et al. 2024) —trade-offs
440 that future advances in low-power electronics and edge computing are likely to mitigate.
441 Targeted improvements in future will come from adaptive schemes for subsampling,
442 reducing and transmitting data.

443 Considering the analysis stage, the integration of expert informed sampling within TABMON
444 helps to make automated recognition into a scalable strategy despite diverse acoustic and
445 environmental conditions (McEwen et al. 2025; Bernard et al. 2025), providing an adaptable
446 blueprint for future large-scale acoustic or multimodal biodiversity networks. Manual
447 validation will continue to be a crucial factor for the interpretability and usability of AI-derived
448 detections in ecological applications, irrespective of future technical improvements.

8.3. Toward integrated and multimodal biodiversity observatories

450 The infrastructure developed through TABMON provides an expandable platform for
451 integrating data from traditional monitoring schemes with sensor-based biodiversity
452 observations (Kissling et al. 2026) Future extensions could couple acoustic sensors with
453 automated camera traps, insect imagers, or eDNA samplers to capture multiple trophic
454 levels and ecological processes (Besson et al. 2022; Wägele et al. 2022). Such multimodal
455 networks could support new EBVs on community composition, phenology, and ecosystem
456 function (Junker et al. 2023). Equally, linking TABMON outputs to existing European
457 initiatives—such as the EuroBirdPortal, LTER-Europe, or the Digital Twin of Nature—would
458 enable dynamic, high-frequency reporting of biodiversity trends, directly informing
459 conservation policy and environmental forecasting.

8.4. Conclusions

461 By demonstrating a functional, harmonized, acoustic monitoring network across Europe,
462 TABMON bridges the gap between conceptual frameworks for continental biodiversity
463 observation and their technical realization by providing a transparent, harmonised and
464 extensible PAM infrastructure. Its methodological advances—in standardized protocols,
465 automated pipelines, and AI validation workflows—provide a foundation that can be readily
466 adopted, scaled, and adapted by other research communities. As biodiversity monitoring
467 enters the era of continuous digital observation, TABMON exemplifies a practical blueprint
468 and a scientific foundation for building continental-scale infrastructures to track biodiversity
469 dynamics via *in situ* sensors.

9. Author contribution

B Cretois, C Rosten, S Sethi, W D Kissling, D Stowell, L Brotons, G Bota, D Villero, R Marxer, and H Glotin contributed to the conceptualization of the project. J Wiel, C Rosten, B Cretois, C Barile, C Bernard, G Bota, L Brotons, C Pérez-Granados, D Villero led the field deployment of the monitoring devices. J Wiel, W D Kissling, C Barile, and C Bernard led the metadata collection and standardization. C Bernard, B McEwen and B Cretois contributed to the design of the analytic pipeline, TABMON dashboard and website. B Cretois led the manuscript writing with input and revisions provided by all coauthors.

10. Acknowledgments

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Supplementary Material S1:

TABMON Site Metadata

In the table below, only a subset of the columns are presented. Please refer to the Supplementary Material S2 "Deployment form" for a full description of the metadata columns.

The columns deploymentID, deploymentGroups, locationName, deploymentStart, deviceHeight, deviceHeading, are expressed as suggested in the Camtrap DP standard adapted to bioacoustics.

Table S1.1 TABMON site metadata description

Country	DeploymentID	Cluster	Site	Active	deploymentBeginDate	deploymentBeginTime	deploymentEndDate	deploymentEndTime	Lat	Lon	Coordinates_uncertainty	GPS_device	DeviceID	Microphone_height	Microphone_direction	Adresse e-mail	Comments
France	20250611_FR_10_e9e2754	Cap Lardier	Prairies	TRUE	11/06/2025	09:45:00			SENSITIVE	SENSITIVE	1	Samsung Galaxy A13 with Google maps	e9e2754	200	South	corentin.bernard@lis-lab.fr	NA
France	20250611_FR_12_adf57530	Cap Lardier	Octopus	TRUE	11/06/2025	12:30:00			SENSITIVE	SENSITIVE	5	Samsung Galaxy A13	adf57530	200	South-West	corentin.bernard@lis-lab.fr	
France	20250611_FR_11_d396add6	Cap Lardier	Gache	TRUE	11/06/2025	11:00:00			SENSITIVE	SENSITIVE	5	Samsung Galaxy A13	d396add6	300	West	corentin.bernard@lis-lab.fr	Close to a the STOC-EPS "Ancienne pinède" point. (2 point counts in spring)
France	20250603_FR_9_22858ce8	Porquerolles	Oustaou	TRUE	03/06/2025	09:00:00			SENSITIVE	SENSITIVE	5	Samsung galax	22858ce8	200	South	corentin.bernard@lis-lab.fr	Close to a bird ringing that uses playback (march 2026)

												y A13					
France	20250603_FR_8_b62a0387	Porquerolles	Lagunes	TRUE	03/06/2025	12:45:00			SENSITIVE	SENSITIVE	1	samsung galaxy A13 with google maps	b62a0387	260	South	corentin.bernard@lis-lab.fr	Bad connection. Close to a bird ringing in the summer that uses playback (march 2026)
France	20250528_FR_6_cc187286	Port-Cros	Palud	TRUE	28/05/2025	08:45:00			SENSITIVE	SENSITIVE	1	Samsung Galaxy A13 with google maps	cc187286	200	South-West	corentin.bernard@lis-lab.fr	Forest near the sea, Close to a the STOC-EPS 831524 (3) point (2 point counts in spring)
France	20250926_FR_7_5b05fe12	Port-Cros	Manoir	TRUE	26/09/2025	10:00:00			SENSITIVE	SENSITIVE	1	Samsung galaxy A13 with google maps	5b05fe12	350	South	corentin.bernard@lis-lab.fr	Moved because of dead tree that needed to be cut. Forest near reed bed and sea, Close to the STOC-EPS 831524 (7) point. (2 point counts in spring)
France	20250514_FR_4_39645e17	Salins des Pesquiers	Salins des Pesquiers North	TRUE	14/05/2025	11:30:00			SENSITIVE	SENSITIVE	1	Samsung galaxy A13 with google maps	39645e17	100	East	corentin.bernard@lis-lab.fr	first deployement with 25ded907 did not work. Alimentation cable cut (rodent?), changed 13/02/2026. Weekly survey
France	20250507_FR_5_3331e641	Salins des Pesquiers	Salins des Pesquiers South	TRUE	07/05/2025	10:30:00			SENSITIVE	SENSITIVE	1	Samsung galaxy A13 with google	3331e641	100	East	corentin.bernard@lis-lab.fr	Weekly survey

Country	ID	Site	Location		Date	Time						Device	Hash		Direction	Email	Notes
												maps					
France	20250310_FR_1_688a86aa	Vieux Salins	Vieux Salins Center	TRUE	10/03/2025	08:45:00			SENSITIVE	SENSITIVE	1	Samsung galaxy A13 with google maps	688a86aa	100	South	corentin.bernard@lis-lab.fr	was recorded by be719bc8 before 2025/05/07. Weekly survey
France	20250310_FR_2_6b3c38e6	Vieux Salins	Vieux Salins East	TRUE	10/03/2025	09:30:00			SENSITIVE	SENSITIVE	1	Samsung Galaxy A13 with google maps	6b3c38e6	100	South	corentin.bernard@lis-lab.fr	was recorded by e9e2754 before 2025/05/07. Weekly survey
France	20250310_FR_3_c1405178	Vieux Salins	Vieux Salins West	TRUE	10/03/2025	10:20:00			SENSITIVE	SENSITIVE	1	Samsung Galaxy A13 with google maps	c1405178	100	South	corentin.bernard@lis-lab.fr	was recorded by d396add6 before 2025/05/07. Problem with alimentation cable connector. Cable changed 13/02/2026. Weekly survey
France	20251027_FR_14_51e1b245	Forêt d'Orient	Osprey nesting pole	TRUE	27/10/2025	10:40:00			SENSITIVE	SENSITIVE	1	Samsung Galaxy A13 with Google maps	51e1b245	280	North	corentin.bernard@lis-lab.fr	
Netherlands	20250130_NL_1_8f06b854	Amsterdamse Waterleidingduinen	van Limburg Stirumvallei X14	TRUE	30/01/2025	11:31:00			SENSITIVE	SENSITIVE	1	Samsung Galaxy S23f e with Goog	8f06b854	100	East	cynthia.barile94@gmail.com	60W solar panel - big pond close by

Netherlands		Amsterdamse Waterleidingduinen										le Maps					
Netherlands	20250130_NL_2_6174ecbe	Amsterdamse Waterleidingduinen	Zilkerpad X9	TRUE	30/01/2025	13:02:00			SENSITIVE	SENSITIVE	1	Samsung Galaxy S23fe with Google Maps	6174ecbe	100	East	cynthia.barile94@gmail.com	60W solar panel. Near path.
Netherlands	20250130_NL_4_9a2290fc	Amsterdamse Waterleidingduinen	Zeeveld Nord X1	TRUE	30/01/2025	15:05:00			SENSITIVE	SENSITIVE	1	Samsung Galaxy S23fe with Google Maps	9a2290fc	100	East	cynthia.barile94@gmail.com	
Netherlands	20250226_NL_3_de594337	Amsterdamse Waterleidingduinen	Zeeveld Zuid X5	TRUE	26/02/2025	08:25:00			SENSITIVE	SENSITIVE	1	Honour Pro 90 with Google Maps	de594337	105	East	cynthia.barile94@gmail.com	50W solar panel - changed location in exclosure for better 4G
Netherlands	20250206_NL_10_30d19c18	Hoge Veluwe	Noordoostelijk van Schaarsbergen X2	TRUE	06/02/2025	11:23:00			SENSITIVE	SENSITIVE	1	Samsung Galaxy S24 with Google Maps	30d19c18	100	East	cynthia.barile94@gmail.com	
Netherlands	20250206_NL_11_63c64349	Hoge Veluwe	Noordoostelijk van Schaarsbergen X3	TRUE	06/02/2025	14:15:00			SENSITIVE	SENSITIVE	1	Honour Pro 90 with Goog	63c64349	100	East	cynthia.barile94@gmail.com	bad 4G connection

											le Maps				
Netherlands	2025020 6_NL_9_4 38d2740	Hoge Veluwe	Noordoo stelijk van Schaarsb ergen X1	TRUE	06/02/2025	10:30:00			SEN SITI VE	SEN SITI VE	1	Hono ur Pro 90 with Goog le Map s	438 d27 40	101	East	cynthia.barile 94@gmail.co m	
Netherlands	2025022 6_NL_5_c fc291d3	Loenderveen	Waterleid ingplas D4	TRUE	26/02/2025	14:11:00			SEN SITI VE	SEN SITI VE	1	Hono ur Pro 90 with Goog le Map s	cfc2 91d 3	96	South	cynthia.barile 94@gmail.co m	Changed direction NL_5
Netherlands	2025020 4_NL_7_f b104ba8	Loenderveen	Waterleid ingplas D2	TRUE	04/02/2025	12:35:00			SEN SITI VE	SEN SITI VE	1	Hono ur Pro 90 with Goog le Map s	fb10 4ba 8	102	West	cynthia.barile 94@gmail.co m	
Netherlands	2025022 6_NL_8_4 4e6e23b	Loenderveen	Waterleid ingplas D1	TRUE	26/02/2025	15:05:00			SEN SITI VE	SEN SITI VE	1	Hono ur Pro 90 with Goog le Map s	44e 6e2 3b	104	East	cynthia.barile 94@gmail.co m	Changed direction NL_8
Netherlands	2025022 6_NL_6_3 b425ce9	Loenderveen	Waterleid ingplas D3	TRUE	26/02/2025	14:30:00			SEN SITI VE	SEN SITI VE	1	Hono ur Pro 90 with Goog le Map s	3b4 25c e9	106	South- East	cynthia.barile 94@gmail.co m	Changed direction NL_6

Netherlands	2025040 1_NL_16_ 9d07fc31	Onlanden	Onlanden (1)	TRUE	01/04/2025	12:24:00			SEN SITI VE	SEN SITI VE	1	Hono ur Pro 90 with Goog le Map s	9d0 7fc3 1	120	North	cynthia.barile 94@gmail.co m	50W solar panel
Netherlands	2025040 1_NL_17_ 3a46c64 6	Onlanden	Onlanden (2)	TRUE	01/04/2025	13:20:00			SEN SITI VE	SEN SITI VE	1	Hono ur pro 90 with Goog le Map s	3a4 6c6 46	132	North-East	cynthia.barile 94@gmail.co m	50W solar panel
Netherlands	2025040 1_NL_18_ 6383061 a	Onlanden	Onlanden (3)	TRUE	01/04/2025	15:16:00			SEN SITI VE	SEN SITI VE	1	Hono ur pro 90 with Goog le Map s	638 306 1a	132	South-West	cynthia.barile 94@gmail.co m	50W solar panel
Netherlands	2025022 5_NL_12_ 498873b 2	Oostvaarders plassen	Drempel D4	TRUE	25/02/2025	11:20:00			SEN SITI VE	SEN SITI VE	1	Hono ur Pro 90 with Goog le Map s	498 873 b2	187	North	cynthia.barile 94@gmail.co m	Adjusted height NL_12
Netherlands	2025022 5_NL_15_ d7a35b3 c	Oostvaarders plassen	Drempel D1	TRUE	25/02/2025	12:35:00			SEN SITI VE	SEN SITI VE	1	Hono ur Pro 90 with Goog le Map s	d7a 35b 3c	188	South	cynthia.barile 94@gmail.co m	50W solar panel
Netherlands	2025022 5_NL_13_ d593cb7 8	Oostvaarders plassen	Drempel D3	TRUE	25/02/2025	11:34:00			SEN SITI VE	SEN SITI VE	1	Hono ur Pro 90 with	d59 3cb 78	197	North-East	cynthia.barile 94@gmail.co m	Adjusted height NL_13

Country																	
												Google Maps					
Netherlands	20250225_NL_14_f0dc521c	Oostvaarders plassen	Drempel D2	TRUE	25/02/2025	13:15:00			SENSITIVE	SENSITIVE	1	Honour Pro 90 with Google Maps	f0dc521c	199	North-East	cynthia.barile94@gmail.com	Adjusted height NL_14
Norway	20250224_NO_26_11d0c4a2	Hamar	Rotlia naturreservat	TRUE	24/02/2025	11:40:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	11d0c4a2	300	East	julia.wiel@nina.no	Microphone height not precise
Norway	20250224_NO_27_932ef8d5	Hamar	RotliaN	TRUE	24/02/2025	13:35:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	932ef8d5	230	North	julia.wiel@nina.no	4G didn't connect
Norway	20250224_NO_28_3e481576	Hamar	Nokleby	TRUE	24/02/2025	15:17:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	3e481576	230	South-West	julia.wiel@nina.no	
Norway	20250225_NO_29_1920e8d5	Hamar	Valetjerne	TRUE	25/02/2025	16:20:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	1920e8d5	250	South	julia.wiel@nina.no	Bad 4G connection
Norway	20250225_NO_30_6a306e76	Hamar	Feltstasjon	TRUE	25/02/2025	18:15:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	6a306e76	235	North	julia.wiel@nina.no	Cow field
Norway	20250228_NO_34_3c943090	Hamar	Akersvika	TRUE	28/02/2025	09:45:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	3c94309d	230	South	julia.wiel@nina.no	
Norway	20250324_NO_36_c7289269	Jaeren	Grudavatnet	TRUE	24/03/2025	08:40:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	c7289269	310	West	julia.wiel@nina.no	
Norway	20250324_NO_37_5bc534f0	Jaeren	Alvevatnet	TRUE	24/03/2025	09:50:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	5bc534f0	185	West	julia.wiel@nina.no	
Norway	20250324_NO_38	Jaeren	Bore	TRUE	24/03/2025	10:50:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	29eb3e1b	240	South	julia.wiel@nina.no	Farm an bushes. Coastal area

	_29eb3e1b																
Norway	20250324_NO_8_3e07ce56	Jaeren	Maleneset	TRUE	24/03/2025	13:30:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	3e07ce56	210	South-East	julia.wiel@nina.no	Changed device only
Norway	20250324_NO_39_941752da	Jaeren	Orre	TRUE	24/03/2025	15:15:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	941752da	230	West	julia.wiel@nina.no	
Norway	20250226_NO_31_d51cd90c	Lillehammer	Gausa	TRUE	26/02/2025	09:48:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	d51cd90c	250	North	julia.wiel@nina.no	Edge of farmland
Norway	20250226_NO_5_2e9f4594	Lillehammer	Svartevjua	TRUE	26/02/2025	12:50:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	2e9f4594	230	North-West	julia.wiel@nina.no	Moved site to get more sun (20m away)
Norway	20250227_NO_4_94dc95d8	Lillehammer	Gropmarka1	TRUE	27/02/2025	13:40:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	94dc95d8	230	East	julia.wiel@nina.no	Redeployed ins the sun. Too much snow for height measurement (only estimate)
Norway	20250227_NO_32_20069731	Lillehammer	Gropmarka2N	TRUE	27/02/2025	17:45:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	20069731	230	South-East	julia.wiel@nina.no	Height not precise due to snow
Norway	20250227_NO_33_2b0e29ef	Lillehammer	Gropmarka2S	TRUE	27/02/2025	18:50:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	2b0e29ef	250	North-West	julia.wiel@nina.no	Height bad
Norway	20250325_NO_6_b91151a3	Lista	Listafuglestasjon	TRUE	25/03/2025	11:00:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	b91151a3	185	West	julia.wiel@nina.no	Changed battery and bugg for v3
Norway	20250325_NO_40_cdfb50bf	Lista	Steinodden	TRUE	25/03/2025	12:10:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	cdfb50bf	210	South	julia.wiel@nina.no	
Norway	20250325_NO_7_5a6ba752	Lista	Slevdalsvannet	TRUE	25/03/2025	14:50:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	5a6ba752	170	South	julia.wiel@nina.no	Battery changes and bugg for v3
Norway	20250325_NO_41_d88bc03a	Lista	Havnehagen	TRUE	25/03/2025	17:40:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	d88bc03a	215	East	julia.wiel@nina.no	

Country	ID	Area	Location	Status	Date	Time			Sens1	Sens2	Count	Device	Code	Value	Direction	Email	Notes
Norway	20240325_NO_42_7e4b3d4f	Lista	Listastrendene	TRUE	25/03/2025	19:25:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	7e4b3d4f	225	South-East	julia.wiel@nina.no	
Norway	20250506_NO_43_6adeac32	Pasvik	Loken	TRUE	06/05/2025	12:34:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	6adeac32	220	East	julia.wiel@nina.no	
Norway	20250506_NO_44_f1c1b1bb	Pasvik	Skoytnes	TRUE	06/05/2025	12:35:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	f1c1b1bb	225	North	julia.wiel@nina.no	In open are pointing to beerch forest
Norway	20250508_NO_50_2f22097	Pasvik	Gjokbukta	TRUE	08/05/2025	08:20:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	2f22097	235	North	julia.wiel@nina.no	
Norway	20250508_NO_51_a1d0792e	Pasvik	Tjaerebukta	TRUE	08/05/2025	09:55:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	a1d0792e	235	South	julia.wiel@nina.no	
Norway	20250508_NO_52_6e4b733f	Pasvik	Skogfoss	TRUE	08/05/2025	12:30:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	6e4b733f	195	North	julia.wiel@nina.no	
Norway	20250130_NO_24_4cb16fa2	Trondelag_1	Tautra farm	TRUE	30/01/2025	10:30:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	4cb16fa2	310	East	julia.wiel@nina.no	
Norway	20250130_NO_25_179e153c	Trondelag_1	Tautra fugletarn	TRUE	30/01/2025	14:20:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	179e153c	255	East	julia.wiel@nina.no	
Norway	20250130_NO_1_eb289bed	Trondelag_1	Auran	TRUE	30/01/2025	17:45:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	eb289bed	220	West	julia.wiel@nina.no	New place. Part of the deployment NO_1_c27ff1cf Auran
Norway	20250116_NO_19_889bef22	Trondelag_2	Leinora	TRUE	16/01/2025	12:27:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	889bef22	205	South	julia.wiel@nina.no	Test for detectability from 12:50 to 14:00 UTC
Norway	20250123_NO_20_1b36a79e	Trondelag_2	Austraatt	TRUE	23/01/2025	10:30:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	1b36a79e	214	North	julia.wiel@nina.no	Long eared owl some years
Norway	20250123_NO_21_22f9afc5	Trondelag_2	GrandefjaeraS	TRUE	23/01/2025	11:20:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	22f9afc5	225	South	julia.wiel@nina.no	Coastal windy

Norway	20250123_NO_22_dc98ad82	Trondelag_2	Grandefjaeran N	TRUE	23/01/2025	14:00:00	21/12/2025	12:00:00	SENSITIVE	SENSITIVE		1	GPS MAP 66sr	dc98ad82		222	South-East	julia.wiel@nina.no	Self-noise when sun on the solar panel. Changed the battery box. Need to check data at 14:00 utc
Norway	20250123_NO_23_8ac55f2f	Trondelag_2	Litlvatnet	TRUE	23/01/2025	17:30:00			SENSITIVE	SENSITIVE		1	GPS MAP 66sr	8ac55f2f		210	East	julia.wiel@nina.no	
Norway	20250310_NO_2_5c75764d	Trondelag_3	Fossvatna	TRUE	10/03/2025	10:30:00			SENSITIVE	SENSITIVE		1	GPS MAP 66sr	5c75764d				julia.wiel@nina.no	No connection
Norway	20240515_NO_3_2efa67ae	Trondelag_4	Roroes	TRUE	15/05/2024	12:57:00			SENSITIVE	SENSITIVE		1	GPS MAP 66sr	2efa67ae				julia.wiel@nina.no	Boreal owl singing every night from ~22-23pm to 5am; from 19.04.2025
Norway	20240526_NO_12_d642707c	Utsira	Svehojen	TRUE	26/05/2024	15:45:00			SENSITIVE	SENSITIVE		1	GPS MAP 66sr	d642707c		240	South-West	julia.wiel@nina.no	
Norway	20250323_NO_13_e848f182	Utsira	Herberg	TRUE	23/03/2025	08:25:00			SENSITIVE	SENSITIVE		1	GPS MAP 66sr	e848f182		254	East	julia.wiel@nina.no	Changed Bugg for V3
Norway	20250323_NO_10_93be5da2	Utsira	Sjoarskogen	TRUE	23/03/2025	10:50:00			SENSITIVE	SENSITIVE		1	GPS MAP 66sr	93be5da2		190	West	julia.wiel@nina.no	Moved because property error. Same forest but on the edge. Turned towards first location
Norway	20250323_NO_35_c27ff1cf	Utsira	Gjenvinningstasjon	TRUE	23/03/2025	13:10:00			SENSITIVE	SENSITIVE		1	GPS MAP 66sr	c27ff1cf		135	South	julia.wiel@nina.no	
Norway	20250323_NO_11_3b0c3815	Utsira	Austre Plantning	TRUE	23/03/2025	14:00:00			SENSITIVE	SENSITIVE		1	GPS MAP 66sr	3b0c3815		215	South-West	julia.wiel@nina.no	Changed Bugg for V3
Norway	20250507_NO_45_826cbf6b	Varanger	Jakobselv skispor	TRUE	07/05/2025	09:25:00			SENSITIVE	SENSITIVE		1	GPS MAP 66sr	826cbf6b		190	North	julia.wiel@nina.no	Data in uploaded in test folder!!! | Height of snow (from ground, at least 250cm)
Norway	20250507_NO_46_eb07ec0c	Varanger	Jakobselv river	TRUE	07/05/2025	10:40:00			SENSITIVE	SENSITIVE		1	GPS MAP 66sr	eb07ec0c		240	South-West	julia.wiel@nina.no	Some snow height imprecise. LED power dead but recorder working well
Norway	20250507_NO_47_4c5b600e	Varanger	Varanger botn naturreservat	TRUE	07/05/2025	12:45:00			SENSITIVE	SENSITIVE		1	GPS MAP 66sr	4c5b600e		200	North-East	julia.wiel@nina.no	Snow height

Country	ID	Site	Location		Date	Time						Device			Direction	Email	Notes
Norway	20250507_NO_48_bc777b7b	Varanger	Varanger botn river	TRUE	07/05/2025	13:45:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	bc777b7b	150	South	julia.wiel@nina.no	Snow height
Norway	20250507_NO_49_77d75946	Varanger_alone	Neiden	TRUE	07/05/2025	15:55:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	77d75946	195	South-West	julia.wiel@nina.no	
Norway	20250513_NO_14_b6b6bc4b	Vega	Igeroya	TRUE	13/05/2025	18:13:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	b6b6bc4b	320	South	julia.wiel@nina.no	retake height, direction, pictures	battery sleep mode activated
Norway	20250514_NO_15_e0269ed6	Vega	Holandsosen	TRUE	14/05/2025	10:54:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	e0269ed6	150	North-East	julia.wiel@nina.no	retake height, direction, pictures
Norway	20250514_NO_18_35ae2bd7	Vega	Kjellarhaugen	TRUE	14/05/2025	12:08:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	35ae2bd7	320	South	julia.wiel@nina.no	retake height, direction, pictures
Norway	20250514_NO_17_82b4e1aa	Vega	Ylvingen	TRUE	14/05/2025	14:08:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	82b4e1aa	350	South-West	julia.wiel@nina.no	retake height, direction, pictures	no SIM card
Norway	20250514_NO_16_c7226535	Vega	Horn	TRUE	14/05/2025	17:08:00			SENSITIVE	SENSITIVE	1	GPS MAP 66sr	c7226535	400	South-West	julia.wiel@nina.no	retake height, direction, pictures	battery sleep mode activated
Spain	20240325_ES_9_379e35d4	Solsones	EDAR	TRUE	25/03/2025	10:00:00			SENSITIVE	SENSITIVE	10	Google maps	379e35d4	150	East	d.villero@creaf.uab.cat	Bugg 379e35d4 located between the tertiary treatment ponds of the Solsona wastewater treatment plant, a stopover point for migratory birds and a nesting area for nocturnal birds of prey.
Spain	20240513_ES_14_7a8e9437	Mas de Melons	Vall de la cisterna	TRUE	13/05/2025	10:00:00			SENSITIVE	SENSITIVE	10	iPhone 13 Mini with Google Maps	7a8e9437	100	East	d.villero@creaf.uab.cat	
Spain	20240513_ES_15_502aab6b	Mas de Melons	La estrella	TRUE	13/05/2025	10:53:00			SENSITIVE	SENSITIVE	10	iPhone 13 Mini with Goog	502aab6b	100	North-West	d.villero@creaf.uab.cat	

												le Maps				
Spain	2024051 3_ES_16_ ad15e51 b	Mas de Melons	Roquisa	TRUE	13/05/2025	12:00:00			SEN SITI VE	SEN SITI VE	10	iPho ne 13 Mini with Goog le Map s	ad1 5e5 1b	100	South	d.villero@crea f.uab.cat	
Spain	2025013 0_ES_18_ 2550e55	Solsones	Castellvel l	TRUE	30/01/2025	00:00:00			SEN SITI VE	SEN SITI VE	10	Sam sung Gala xy 22+ with Goog le Map s	255 0e5 5	500	West	d.villero@crea f.uab.cat	
Spain	2025021 9_ES_1_b 5812468	Delta del Ebre	Canal Vell	TRUE	19/02/2025	09:00:00			SEN SITI VE	SEN SITI VE	10	iPho ne 13 Mini with Goog le Map s	b58 124 68	100	South	d.villero@crea f.uab.cat	Next to ringed migratory birds station in autumn/summer.
Spain	2025021 9_ES_2_3 6308864	Delta del Ebre	Buda	TRUE	19/02/2025	11:00:00			SEN SITI VE	SEN SITI VE	10	iPho ne 13 Mini with Goog le Map s	363 088 64	350	East	d.villero@crea f.uab.cat	Need to come back to adjust BUGG for long term placement. Near ringed birds. Longterm placement adjustment on 11/03/2025
Spain	2025031 1_ES_3_8 e7fead8	Delta del Ebre	L'alfacad a	TRUE	11/03/2025	09:20:00			SEN SITI VE	SEN SITI VE	10	iPho ne 13 Mini with Goog le Map s	8e7f ead 8	105	West	d.villero@crea f.uab.cat	Deployment Bugg ES_3_8e7fead8 relocated on 03/11/2025 to this new location
Spain	2025031 1_ES_4_4 9da8233	Delta del Ebre	La tancada	TRUE	11/03/2024	11:45:00			SEN SITI VE	SEN SITI VE	10	iPho ne 13 Mini with Goog	49d a82 33	108	South	d.villero@crea f.uab.cat	Looks as if the bugg is not able to connect to data but then turns blue, left device with connection. In very

Spain												le Maps					windy area, yearly bird festival (september)
Spain	20250320_ES_5_55dc62ae	AiguamollsEmporda	Mata	TRUE	20/03/2025	10:29:00			SENSITIVE	SENSITIVE	10	Oppo A40 with Google Maps	55dc62ae	140	South-East	d.villero@creaf.uab.cat	
Spain	20250320_ES_7_1c1dcfe8	AiguamollsEmporda	Rogera	TRUE	20/03/2025	14:20:00			SENSITIVE	SENSITIVE	10	Oppo A40 with Google Maps	1c1dcfe8	120	North	d.villero@creaf.uab.cat	
Spain	20250320_ES_8_613266b	AiguamollsEmporda	Palau	TRUE	20/03/2025	16:53:00			SENSITIVE	SENSITIVE	10	Oppo A40 with Google Maps	613266b	120	North-East	d.villero@creaf.uab.cat	
Spain	20250411_ES_10_a88572f	Osona	Colomer	TRUE	11/04/2025	08:51:00			SENSITIVE	SENSITIVE	10	iPhone 13 Mini with Google Maps	a88572f	400	North	d.villero@creaf.uab.cat	Office tests between 15/05/2025 and 09/06/2025 at 6:00UTC. Put back in field on 09/06/2025 at 8:00UTC
Spain	20250411_ES_11_91d7198e	Osona	Collell	TRUE	11/04/2025	09:48:00			SENSITIVE	SENSITIVE	10	iPhone 13 Mini with Google Maps	91d7198e	170	South	d.villero@creaf.uab.cat	
Spain	20250411_ES_13_f1a26bc9	Osona	Vilacís	TRUE	11/04/2025	11:37:00			SENSITIVE	SENSITIVE	10	iPhone 13 Mini with Google Maps	f1a26bc9	450	North	d.villero@creaf.uab.cat	Office tests between 15/05/2025 and 09/06/2025 at 6:00UTC. Put back in field on 09/06/2025 at 8:00UTC but no conection? Stopped sending data on Jun25. Field visit needed.

Spain	20250516_ES_6_4035de5	AiguamollsEmporda	Cortalet	TRUE	16/05/2025	00:00:00			SENSITIVE	SENSITIVE	10	Oppo A40 with Google Maps	4035de5	100	South	d.villero@creaf.uab.cat	Replacement of BUGG ES_6_2d00da80
Spain	20250701_ES_17_2d00da80	Mas de Melons	Cabana l'Era	TRUE	01/07/2025	10:50:00			SENSITIVE	SENSITIVE	10	iPhone 13 Mini with Google Maps	2d00da80	200	East	d.villero@creaf.uab.cat	BUGG that was recording before at station in Cortalet - AiguamollsEmporda, now moved to new station here at station Cabana l'Era - Mas de Melons
Spain	20251024_ES_12_c5a44da9	Osona	Can Talaia	TRUE	24/10/2025	10:00:00			SENSITIVE	SENSITIVE	10	Samsung Galaxy 22+ with Google Maps	c5a44da9	150	South-East	mar.escobar@ctfc.cat	Deployment Bugg ES_12_c5a44da9 relocated on 24/10/2025 to this new location
France	20251121_FR_19_25ded907	Calanques	Carpiagne	TRUE	21/11/2025	12:45:00			SENSITIVE	SENSITIVE	5	Samsung galaxy A13 with google maps	25ded907	270	South-East	corentin.bernard@lis-lab.fr	
France	20251211_FR_18_c2d07a70	Calanques	Cap Canaille	TRUE	11/12/2025	15:30:00			SENSITIVE	SENSITIVE	5	Samsung Galaxy A13 with google maps	c2d07a70	300	South	corentin.bernard@lis-lab.fr	
France	20251212_FR_20_75707515	Calanques	Île du Planier	TRUE	12/12/2025	10:30:00			SENSITIVE	SENSITIVE	1	Samsung Galaxy A13	75707515	450	South	corentin.bernard@lis-lab.fr	

France	2025121 2_FR_21_ 38742b7	Calanques	Vallon de l'Agneau	TRUE	12/12/2025	15:30:00			SEN SITI VE	SEN SITI VE	5	Sam sung Gala xy A13 with goog le map s	387 42b 7	400	South	corentin.bern ard@lis-lab.fr	
France	2026017 _FR_15_b 82f0734	Forêt d'Orient	Charlieu	TRUE	07/01/2026	17:00:00			SEN SITI VE	SEN SITI VE	10	Smar tpho ne with Goog le map s	b82f 073 4	400	South	corentin.bern ard@lis-lab.fr	Installed by Stephane GAILLARD
France	2026011 9_FR_16_ be719bc 8	Forêt d'Orient	Rappel-coeur	TRUE	19/01/2026	14:00:00			SEN SITI VE	SEN SITI VE	10	Smar tpho ne with Goog le map s	be7 19b c8	400	South-East	corentin.bern ard@lis-lab.fr	Installed by Stephane GAILLARD
France	2026011 9_FR_17_ 9c83ff07	Forêt d'Orient	Marmore t	TRUE	19/01/2026	16:00:00			SEN SITI VE	SEN SITI VE	10	Smar tpho ne with Goog le map s	9c8 3ff0 7	300	South-West	corentin.bern ard@lis-lab.fr	Installed by Stephane GAILLARD
France	2026011 9_FR_13_ f12e34b2	Forêt d'Orient	Valois	TRUE	19/01/2026	18:00:00			SEN SITI VE	SEN SITI VE	10	Smar tpho ne with Goog le map s	f12e 34b 2	1200	South-East	corentin.bern ard@lis-lab.fr	Previously 20251027_FR_13_f12e34b2 - Grand Orient. Moved because no connection. Installed by Stephane GAILLARD

Figure S1.1: Boxplots displaying the pairwise distances between devices within individual clusters for each country.

Within-cluster distances

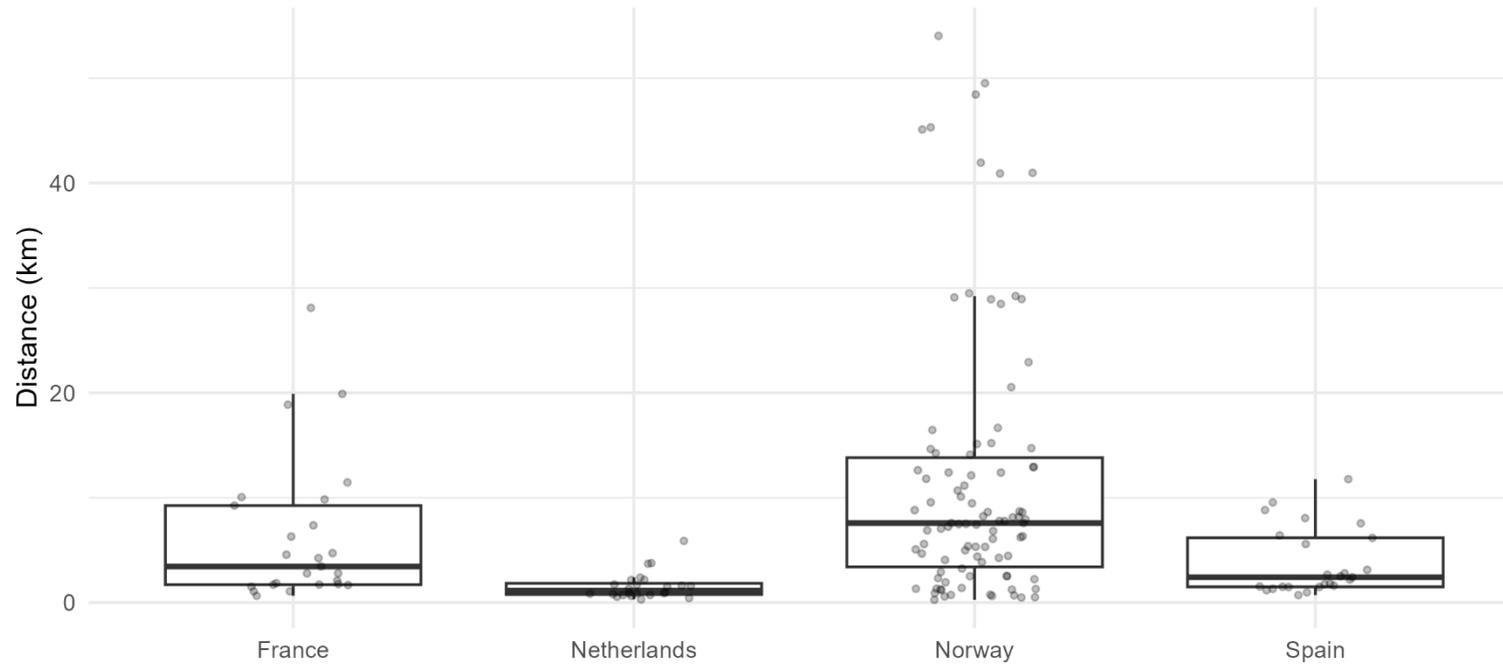Pairwise distances between devices within each cluster

Table S1.2: Distance between each devices within clusters.

Cluster Name	device_a	device_b	Distance (in km)	Country
AiguamollsEmporda	4035de5	1c1dcfe8	1.52	Spain
AiguamollsEmporda	55dc62ae	1c1dcfe8	1.5	Spain
AiguamollsEmporda	55dc62ae	4035de5	1.54	Spain
AiguamollsEmporda	613266b	1c1dcfe8	6.42	Spain
AiguamollsEmporda	613266b	4035de5	6.18	Spain
AiguamollsEmporda	613266b	55dc62ae	7.57	Spain
Amsterdamse Waterleidingduinen	8f06b854	6174ecbe	2.16	Netherlands
Amsterdamse Waterleidingduinen	9a2290fc	6174ecbe	3.77	Netherlands
Amsterdamse Waterleidingduinen	9a2290fc	8f06b854	5.89	Netherlands
Amsterdamse Waterleidingduinen	de594337	6174ecbe	1.59	Netherlands
Amsterdamse Waterleidingduinen	de594337	8f06b854	3.71	Netherlands
Amsterdamse Waterleidingduinen	de594337	9a2290fc	2.19	Netherlands
Cap Lardier	d396add6	adf57530	1.68	France
Cap Lardier	e9e2754	adf57530	1.71	France
Cap Lardier	e9e2754	d396add6	0.66	France
Delta del Ebre	49da8233	36308864	9.55	Spain
Delta del Ebre	8e7fead8	36308864	2.53	Spain
Delta del Ebre	8e7fead8	49da8233	8.83	Spain
Delta del Ebre	b5812468	36308864	5.59	Spain
Delta del Ebre	b5812468	49da8233	11.78	Spain
Delta del Ebre	b5812468	8e7fead8	8.06	Spain
Hamar	1920e8d5	11d0c4a2	8.14	Norway
Hamar	3c94309d	11d0c4a2	16.46	Norway
Hamar	3c94309d	1920e8d5	10.11	Norway
Hamar	3e481576	11d0c4a2	5.32	Norway

Hamar	3e481576	1920e8d5	4.68	Norway
Hamar	3e481576	3c94309d	11.16	Norway
Hoge Veluwe	438d2740	30d19c18	0.32	Netherlands
Hoge Veluwe	63c64349	30d19c18	0.44	Netherlands
Hoge Veluwe	63c64349	438d2740	0.56	Netherlands
Jaeren	3e07ce56	29eb3e1b	4.27	Norway
Jaeren	5bc534f0	29eb3e1b	2.57	Norway
Jaeren	5bc534f0	3e07ce56	6.84	Norway
Jaeren	941752da	29eb3e1b	5.39	Norway
Jaeren	941752da	3e07ce56	1.2	Norway
Jaeren	941752da	5bc534f0	7.94	Norway
Jaeren	c7289269	29eb3e1b	4.46	Norway
Jaeren	c7289269	3e07ce56	7.51	Norway
Jaeren	c7289269	5bc534f0	3.86	Norway
Jaeren	c7289269	941752da	8.24	Norway
Lillehammer	2b0e29ef	20069731	0.52	Norway
Lillehammer	2e9f4594	20069731	7.24	Norway
Lillehammer	2e9f4594	2b0e29ef	6.9	Norway
Lillehammer	94dc95d8	20069731	3.26	Norway
Lillehammer	94dc95d8	2b0e29ef	2.93	Norway
Lillehammer	94dc95d8	2e9f4594	8.18	Norway
Lillehammer	d51cd90c	20069731	7.78	Norway
Lillehammer	d51cd90c	2b0e29ef	7.59	Norway
Lillehammer	d51cd90c	2e9f4594	2.51	Norway
Lillehammer	d51cd90c	94dc95d8	9.56	Norway
Lista	7e4b3d4f	5a6ba752	12.41	Norway
Lista	b91151a3	5a6ba752	2.24	Norway
Lista	b91151a3	7e4b3d4f	14.64	Norway
Lista	cdfb50bf	5a6ba752	2.33	Norway

Lista	cdfb50bf	7e4b3d4f	14.73	Norway
Lista	cdfb50bf	b91151a3	0.5	Norway
Lista	d88bc03a	5a6ba752	5.33	Norway
Lista	d88bc03a	7e4b3d4f	7.79	Norway
Lista	d88bc03a	b91151a3	7.49	Norway
Lista	d88bc03a	cdfb50bf	7.44	Norway
Loenderveen	44e6e23b	3b425ce9	1.69	Netherlands
Loenderveen	cfc291d3	3b425ce9	0.73	Netherlands
Loenderveen	cfc291d3	44e6e23b	1.73	Netherlands
Loenderveen	fb104ba8	3b425ce9	0.9	Netherlands
Loenderveen	fb104ba8	44e6e23b	0.81	Netherlands
Loenderveen	fb104ba8	cfc291d3	0.98	Netherlands
Mas de Melons	502aab6b	2d00da80	1.76	Spain
Mas de Melons	7a8e9437	2d00da80	1.19	Spain
Mas de Melons	7a8e9437	502aab6b	2.67	Spain
Mas de Melons	ad15e51b	2d00da80	1.62	Spain
Mas de Melons	ad15e51b	502aab6b	1.32	Spain
Mas de Melons	ad15e51b	7a8e9437	2.8	Spain
Onlanden	6383061a	3a46c646	1.32	Netherlands
Onlanden	9d07fc31	3a46c646	0.73	Netherlands
Onlanden	9d07fc31	6383061a	0.65	Netherlands
Oostvaardersplassen	d593cb78	498873b2	0.9	Netherlands
Oostvaardersplassen	d7a35b3c	498873b2	2.4	Netherlands
Oostvaardersplassen	d7a35b3c	d593cb78	1.51	Netherlands
Oostvaardersplassen	f0dc521c	498873b2	1.62	Netherlands
Oostvaardersplassen	f0dc521c	d593cb78	0.85	Netherlands
Oostvaardersplassen	f0dc521c	d7a35b3c	0.88	Netherlands
Osona	a88572f	91d7198e	0.99	Spain
Osona	c5a44da9	91d7198e	2.22	Spain

Osona	c5a44da9	a88572f	3.14	Spain
Osona	f1a26bc9	91d7198e	1.49	Spain
Osona	f1a26bc9	a88572f	2.43	Spain
Osona	f1a26bc9	c5a44da9	0.73	Spain
Pasvik	6adeac32	2f22097	45.31	Norway
Pasvik	6e4b733f	2f22097	28.94	Norway
Pasvik	6e4b733f	6adeac32	16.67	Norway
Pasvik	a1d0792e	2f22097	4.39	Norway
Pasvik	a1d0792e	6adeac32	45.11	Norway
Pasvik	a1d0792e	6e4b733f	28.48	Norway
Pasvik	f1c1b1bb	2f22097	40.91	Norway
Pasvik	f1c1b1bb	6adeac32	4.99	Norway
Pasvik	f1c1b1bb	6e4b733f	12.92	Norway
Pasvik	f1c1b1bb	a1d0792e	40.97	Norway
Porquerolles	b62a0387	22858ce8	1.52	France
Port-Cros	cc187286	5b05fe12	1.09	France
Salins des Pesquiers	39645e17	3331e641	1.72	France
Solsones	379e35d4	2550e55	1.81	Spain
Trondelag_1	4cb16fa2	179e153c	1.34	Norway
Trondelag_1	eb289bed	179e153c	12.13	Norway
Trondelag_1	eb289bed	4cb16fa2	12.63	Norway
Trondelag_2	22f9afc5	1b36a79e	8.63	Norway
Trondelag_2	889bef22	1b36a79e	48.44	Norway
Trondelag_2	889bef22	22f9afc5	49.51	Norway
Trondelag_2	8ac55f2f	1b36a79e	10.69	Norway
Trondelag_2	8ac55f2f	22f9afc5	7.59	Norway
Trondelag_2	8ac55f2f	889bef22	41.94	Norway
Trondelag_2	dc98ad82	1b36a79e	8.7	Norway
Trondelag_2	dc98ad82	22f9afc5	5.08	Norway

Trondelag_2	dc98ad82	889bef22	54.03	Norway
Trondelag_2	dc98ad82	8ac55f2f	12.4	Norway
Utsira	93be5da2	3b0c3815	0.59	Norway
Utsira	c27ff1cf	3b0c3815	0.28	Norway
Utsira	c27ff1cf	93be5da2	0.65	Norway
Utsira	d642707c	3b0c3815	0.91	Norway
Utsira	d642707c	93be5da2	0.74	Norway
Utsira	d642707c	c27ff1cf	0.7	Norway
Utsira	e848f182	3b0c3815	1.33	Norway
Utsira	e848f182	93be5da2	0.76	Norway
Utsira	e848f182	c27ff1cf	1.41	Norway
Utsira	e848f182	d642707c	1.27	Norway
Varanger	826cbf6b	4c5b600e	29.1	Norway
Varanger	bc777b7b	4c5b600e	1.94	Norway
Varanger	bc777b7b	826cbf6b	29.49	Norway
Varanger	eb07ec0c	4c5b600e	28.92	Norway
Varanger	eb07ec0c	826cbf6b	1.31	Norway
Varanger	eb07ec0c	bc777b7b	29.23	Norway
Vega	82b4e1aa	35ae2bd7	13.03	Norway
Vega	b6b6bc4b	35ae2bd7	7.35	Norway
Vega	b6b6bc4b	82b4e1aa	6.33	Norway
Vega	c7226535	35ae2bd7	21.73	Norway
Vega	c7226535	82b4e1aa	8.82	Norway
Vega	c7226535	b6b6bc4b	15.13	Norway
Vieux Salins	6b3c38e6	688a86aa	1.86	France
Vieux Salins	c1405178	688a86aa	1.08	France
Vieux Salins	c1405178	6b3c38e6	2.8	France

Supplementary material S2:
Deployment form

This document describes the metadata we collect when a TABMON site is deployed. We use a Google Form to fill in the information on the field.

Metadata description

Country
In which country is the deployment taking place?

DeploymentID
deploymentBeginDate_countryCode_deploymentNumber_DeviceID (e.g. 20250224_NO_1_7ft35sm)

This standardised ID will refer to each individual deployment.
- deploymentBeginDate: 20250224
- countryCode: FR = France, NL = Netherlands, NO = Norway, ES = Spain,
- deploymentNumber: to identify the number of the deployment (increment per country). *E.g.: for the 4th deployment in Spain, the deploymentNumber should be: 4.*
- DeviceID: copy paste the DeviceID field.

Cluster
Name of the cluster the device is being deployed in.

Site
The name, or an identification of the site (within the cluster) the device is being deployed at.

Active
Tick TRUE.
If the current deployment consists in *replacing/moving* a Bugg, or any situation that needs a new deploymentID, making a pre-existing one obsolete, remember to change the previous deploymentID to "FALSE" (= this deployment is no longer active), and to indicate date and time at which you ended the deployment ('deploymentEndDate' and 'deploymentEndTime' columns). Do this directly in the Bugg deployment form (response) table. See "New Deployment ID" section below for more details.

deploymentBeginDate
Date of deployment.

deploymentBeginTime
Write the time at which you started the device. **Please make sure you DO NOT use local time but UTC!** https://www.utctime.net/

Latitude

Geodetic datum should be WGS84. If you're using Google Maps on your phone, it is the default. Verify if you are using any other app/device, make sure it is set to WGS84. Latitude in decimal degrees, *e.g.* 52.370216.

Longitude
See above.

Coordinates uncertainty
Write the uncertainty of the position, in meters. Hand-held GPS will give you this value. If using phone GPS : 20 m. If using localisation on satellite images : 1 m

GPS device
What device did you use to record the position of the device? *E.g.* Garmin 63r, Samsung Galaxy S24 with Google Maps

DeviceID
Last digits of the serial number.
If your device RPiID is: 100000007ft35sm, please write: 7ft35sm.
The serial number of the Bugg can be found on the back of the device (see the picture attached on the right). If your device does not have a sticker (older Bugg version), you can find this number in the Google bucket and file name.

Microphone height
In cm. Measure the height of the microphone (see picture to see where the microphone is located). When possible, aim for a minimum height of 2 meters.
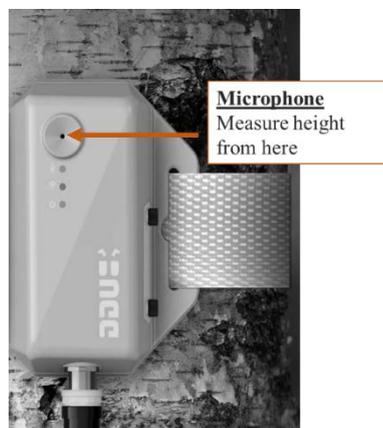
Microphone_direction

Placing your compass above the Bugg to get the general direction towards which the microphone is pointing. Select direction from the drop-down menu.

Habitat
Select which habitat you are deploying the device in. If it does not fit any of the categories, select 'Other' and specify.

Comments:
Write here anything you find relevant.

How to take photos

To have a visual representation of the surrounding environment, **7 pictures** should be taken for each deployment. Take the following pictures (in landscape format):
- 4 pictures of the surroundings, standing 2 metres away from Bugg. Keep the Bugg in the picture frame: **(i)** in the same direction as the microphone (*front)*, **(ii)** the right of the microphone direction (*right)*, **(iii)** the left of the microphone direction (*left)*, **(iv)** the back of the microphone direction (*back)*.
- **(v)** 1 picture pointing upward (towards the sky), taken from the top of the device (*up)*. **(vi)** 1 picture pointing downward (towards the ground), taken from the device height (*down*).
- **(vii)** 1 picture of the device itself, ~5 metres away (*device).*

Rename the pictures as follows: deploymentID_Direction.
    Get the DeploymentID from the form.
    Direction {front, back, left, right, up, down, device}
    E.g.: **NO_1_7ft35sm_front**

New deploymentID for a same site

A new deploymentID can be generated in the three following cases:
- The settings are changed in the config.json
- The device is replaced by another one
- The device is moved a few meters away from the initial location

DeploymentID: YYYYMMDD_COUNTRYCODE_NUMBER_DeviceID

Example 1: The device is replaced by another one. The country code and the number are the same. The date and the DeviceID are updated
    ex: 20241003_NO_1_gdtesjx → 20250426_NO_1_7ft35sm

Example 2: The settings are changed or the device is moved a few meters away. The country code, the number and DeviceID remain the same. The date is updated.
    ex: 20241003_NO_1_gdtesjx → 20250426_NO_1_gdtesjx

Supplementary material S3:

From continental criteria to country level strategy

1. TABMON strategy

1.1 Criteria

In the first months of the project, the consortium agreed on a set of broad criteria to select suitable sites. The sites were ultimately selected by each partner in their own country. The two main objectives are (i) to **cover gaps in current bird monitoring programs**, and (ii) to focus on the **phenology of the migration**. The monitoring programs are different in each country, and so are the gaps to fill. The species and habitats selected are therefore not identical. Furthermore, due to the large latitudinal coverage, the consortium could not define specific habitats in which to collect the data. Additionally, it was not possible to select a short list of species before obtaining detections from the AI model: indeed, we need to know first which species we are able to detect. These constraints add to the logistical consideration (number of devices, vandalism, partner resource for data collection, etc.).
Nevertheless, the following criteria were established to guide the site selection process from the consortium to the country level.

- **Species of interest**

Among the gaps shared by all the countries in the consortium, we identified the following aspects regarding the target species and habitats.

Species among the migratory passeriformes are present in all countries. We can enhance the precision of the AI model for common species that are already fairly well detected by existing ML models (e.g. Birdnet), and aim for better reliability in the detection of cryptic species through model refinement.

Night-active species are not well covered by existing monitoring schemes. BirdNet is pretty accurate for some species (e.g. Scop owl, Eagle owl, Nightjar), and doesn't perform well for others (e.g. Tawny owl; see Supplementary Material S5). The priorities for this group are to assess how PAM can contribute to better monitoring night-active species, and to refine the model for the species currently poorly detected and classified by existing models.

- **Habitat**

The definition of habitat in the consortium is very broad to overcome the lack of comparability between biomes located across a large latitudinal gradient. The sites can be deployed across wetland, forest, and coastal habitats. The two main criteria are:

- Open habitats characterised by a low vegetation density (reedbeds, wetland, etc.)
- Closed habitats characterised by a high vegetation density (deciduous and evergreen forest, bushes, etc.)

- **Cluster**

One cluster corresponds to one geographical unit containing suitable habitat for migrant passerines and nocturnal birds as identified by local ornithologists. The clusters improve logistical efficiency for the installation and maintenance of the devices while increasing data robustness, as recordings from multiple devices within a cluster can partially compensate for temporary device failures.

Within a cluster, the sound recorders must be placed such that a signal recorded at one microphone cannot be simultaneously detected by another microphone, with a minimum distance of about 250 meters between them.

1.2 European migrant terrestrial birds flyways and TABMON sites location (credit to [Diego Pavón-Jordán](#))

Figure S3.1: TABMON site locations are shown in blue with the number of devices indicated when more than one is present. The red arrows represent the main spring migration flyways of terrestrial birds across Europe between Spain, France, The Netherlands and Norway.

1.3 Prior consideration for the site selection per country

1.3.1 What country specific requirements/limitations are there? (e.g. restrictions for data collection regarding GDPR, physical or geographical limitations)

Norway

In terms of GDPR in Norway, we have previously ([The Sound of Norway](#)) obtained permission from landowners to deploy devices, deployed devices so that they are out of range of areas commonly frequented by people (near buildings, car parks, etc.), installed a sign at each recording site informing people that we are recording sound and providing information about the project. For TABMON, the decision is to not share publicly raw data (full audio files and clips) that could potentially contain human speech.

Physical limitations include extremely remote locations that may not be feasible for this study, limited road coverage, meaning that many areas, while not extremely remote, are still many kilometres from the nearest road, snow for several months in winter, which may limit whether equipment can be installed year-round, short or no daylight in winter, precluding the use of solar panels for power during winter for year-round installation.

The Netherlands

For the Dutch component of the TABMON project, the deployment and operation of acoustic sensors must comply with the GDPR (EU Regulation 2016/679), particularly regarding the potential recording of personal data such as human speech. Permission from landowners is obtained prior to sensor installation, and landowners agree to assist with installation and maintenance where necessary.

Site selection prioritizes locations with minimal human presence to reduce the likelihood of recording identifiable personal information; devices are therefore placed as much as possible in areas rarely frequented by the public, such as exclosures in forests and coastal scrublands, and protected wetland reserves that are generally inaccessible.

Audio recordings that may contain human voices are treated as sensitive data. Any sharing of raw audio files collected by the Dutch partner outside the consortium requires careful handling and, where necessary, specific data-sharing agreements developed in consultation with legal advisors.

France

All sites are deployed in protected areas on lands owned and managed by public organisations. The sites in the region of Toulon, near our research facility, are deployed first to facilitate preliminary testing of the sound recording system.

The sites are deployed as far as possible from human activity, yet with connectivity and easy access by foot to carry the material.

In terms of human speech, the same actions as Norway are adopted: obtain landowner permission, deploy far from human activities, install a sign with project information, and not share publicly raw data.

Geographical limitations are mainly due to time limitations of the dedicated staff.. The south and south-east coast of France and the Rhône valley are the easiest to access. Sites on the Atlantic coast were considered but could not be selected. Instead, we prioritised transnational network continuity by deploying additional sites mid-way between the south of France and the Netherlands, near Troyes in the Forêt d'Orient, a well-known stop-over place for migrant birds.

Physical limitations are strong winds in coastal areas (noise), high temperatures on the southern coast (battery), and low temperatures (battery) and snow (solar panel) in the Pyrenees.

Spain

In terms of GDPR in Spain, in previous studies we have collaborated mainly with public administrations and protected areas and obtained official permissions to deploy devices in the field, but the Spanish GDPR regulation has been recently implemented and there is still a long way to go to better understand the implications related to the application of new technologies in field studies.

We have no major physical limitations for deploying Bugg devices in the field, and the main geographical limitations may be access to remote areas not covered by existing bird monitoring programs or affected by wildfires.

1.3.2 Which existing national monitoring programs might we link to (by country)?

Norway

- The Norwegian Breeding Bird Survey led by NINA with Birdlife Norge and the Norwegian Environmental Agency. It is the most important project for monitoring population trends for Norwegian bird species on land.
- Migratory bird observatories on the south coast: Lista fuglestasjon and Utsira fuglestasjon
- Biodiversa VisAviS project which uses radars to monitor migratory bird movements through Norway related to the development of offshore energy installation.
- Artsobservasjoner – National species observation system based on citizen science.

The Netherlands

In the Netherlands, acoustic monitoring within TABMON can be linked to existing national bird monitoring programs coordinated by SOVON Dutch Centre for Field Ornithology. SOVON manages the country's standardized bird monitoring schemes, including territory mapping, transect counts, point counts, and waterbird censuses. As a project partner,

SOVON can provide an overview of available monitoring data from these programs and facilitate access where needed, enabling the integration and comparison of acoustic monitoring results with established national biodiversity monitoring datasets.

France

- [La Ligue pour la Protection des Oiseaux](#): French representative of Birdlife International.
- [Mission Migration](#): network of associations, working together to improve the protection of migrants and the conservation of their habitat.
- [The project Provence Grand Large](#): the University of Toulon contributes to the environmental monitoring related to the installation of windfarms offshore.
- [STOC](#) inventory: Temporal monitoring of common birds based on citizen science.
- [Trektellen](#): european platform to share migration counts, captures, and nocturnal flight calls

Spain

- [Ornitho.cat](#), online platform for recording species observations and lists based on citizen science integrated into the EuroBirdPortal platform
- Catalan Common Bird Long-term Monitoring program (SOCC)
- Catalan Nocturnal Bird Monitoring program (SONC)
- Recording nocturnal bird migration (NOCMIG)
- DINDIS, Monitoring bird communities affected by large wildfires in Mediterranean landscapes
- FarmDINDIS, Monitoring steppe bird communities in semi-arid Mediterranean agricultural systems

1.3.3 What spatial, temporal and taxonomic gaps are identified by avian specialists (e.g. for avian migration phenology, species distribution and population abundance)

Norway

-   Key taxonomic groups include wetland species, nocturnal species, rare species, and migratory species.
-   The phenology was identified as a priority gap in current monitoring systems, particularly migration phenology.
-   Migration behaviour: continued migration vs settlement within an area.

The Netherlands

In the Netherlands, we have identified several spatial, temporal, and taxonomic monitoring gaps that acoustic monitoring within TABMON could help address. Taxonomically, gaps exist for rare, cryptic, or inconspicuous species, particularly nocturnal birds such as rails, bitterns, owls, and nightjars, as well as secretive species like partridges that are often underdetected in conventional surveys. This is especially relevant for wetland species associated with reedbeds and marshes (e.g., water rail, spotted crake, Baillon's crake, and

Eurasian bittern), as well as other focal species of conservation concern in Natura 2000 sites, including Savi's warbler, several woodpeckers, European nightjar, woodlark, and northern wheatear. Spatial gaps occur in remote or difficult-to-access habitats, particularly wetlands and dense reedbeds, but also in agricultural landscapes where volunteer coverage is low and in coastal scrublands that may serve as migration corridors. Temporally, nocturnal activity and migration phenology remain insufficiently monitored for many species. Passive acoustic monitoring therefore offers opportunities to improve detection and monitoring of these taxa and habitats while complementing existing bird monitoring schemes.

France

The stakeholders from the national and regional parks highlighted the following points of interest:
- Occupancy by sector
- Nocturnal species
- Nocturnal migratory species
- Rare species
- Monitoring of nocturnal and diurnal acoustic migration and trend monitoring of local breeding species.

In addition, the following groups were highlighted:
- Orthopteres endemic worldwide (4-5 species)
- Standardised surveys of orthopterans with estimates of abundance

Spain

Key taxonomic groups include wetland, farmland, forest, nocturnal, and migratory species. Main spatial and temporal gaps in monitoring programs are related mainly to the recording of non-breeding and migratory data.

1.3.4 What study design needs to be considered based on the number of devices available in each country/throughout the transnational network?

Norway

In Norway 51 devices are available. This will not be enough to provide statistically representative data for questions related to species distribution or population abundance (at scale relevant to a transnational project). The ornithology group at NINA is very interested in questions regarding phenology, particularly migration phenology. This is a gap that is not covered by any existing national monitoring program. The use of radar systems to monitor migrations (currently being tested in VisAvis Biodiversa project funded in 2022) lacks species specific information, so acoustics could complement both radar and human observations as a way to identify species.

The study design for Norway focuses on the south coast of Norway (Lista, Jæaren, Utsira) and the north tip (Varanger, Pasvik) where most of the migrant species are stopping over or breeding. Additional clusters are placed more centrally in Innlandet, Trøndelag and Vega in known stop-over places.

This approach could be mirrored in the other countries by grouping devices in areas with high expected levels of migratory species activity.

The Netherlands

The study design in the Netherlands is constrained by the availability of 18 Bugg acoustic devices, limited by national funding for equipment. To balance spatial coverage and logistical feasibility, sensors are distributed across five study sites, typically forming clusters of 3–4 devices per site to allow within-site comparisons and improve detection reliability. The selected sites represent both replicated habitats (three wetland sites) and contrasting habitat types (wetlands, coastal scrubland, and forest), enabling comparisons across habitat conditions as well as among sites within a habitat type. The design also ensures coverage of both open and closed habitats (e.g. wetlands and scrublands versus forest). Site selection and sensor placement further considered security risks, favoring locations where equipment could be installed in relatively secure areas to reduce theft or damage. Finally, the total number of sites is kept limited to ensure that installation, maintenance, and data retrieval remain feasible given the available personnel and logistical capacity.

France

A design to provide the occupancy by sector is too ambitious given the number of devices. The strategy in France consists in spreading the devices along areas with high migration activities to capture general migratory trends. For instance, along the Mediterranean coastline and in the Forêt d'Orient further North inland.

Spain

In Catalonia we have 20 Bugg devices that are used to cover spatial and temporal gaps for recording standardised species lists in Ornitho.cat data (within the EuroBirdPortal framework) or NOCMIG, but also to test and complement existing regional monitoring schemes, such as SOCC and SONC. In the CTFC we also have a strong background in monitoring bird communities in both mediterranean landscapes affected by wildfires and semi-arid agricultural systems, and we are very interested in the potential to complement ongoing monitoring programs with bioacoustics.

1.4 Species list

The TABMON network spans a large latitudinal region with species and habitats that are not necessarily comparable one-to-one. Moreover, the species of interest at the country level might differ from one another depending on existing national monitoring schemes. Given that the data workflow is shared among all the partners, a common ground needs to be defined to ensure that the data produced by all three workpackages are compatible.

For instance, among the work packages criteria, we note that for WP1, the species must be vocal and detectable by the sound recorder. For WP2, the AI model must detect its call in the sound file and reliably classify it: this is assessed through manual validation. And for WP3, enough classified samples must be available for a given species with high reliability to draw ecological conclusions, and the new information must fill gaps in the EBV cube.

1.4.1 Species guidance for WP1 site selection

TABMON focuses on the phenology of migration of terrestrial birds (migrant passerines) and night-active birds which are detectable in more than one country of the consortium. In **Table S3.1,** we summarize what information has been considered to include a species in the preliminary species list. This list has been used mainly to guide WP1 in the site selection. It is a rough selection to narrow down what habitat to target.

Table S3.1: Description of the information collected in the preliminary species list for WP1 site selection.

Column Name	Rationale
EURING	Description: European standard coding system for observations on marked birds. Here, the code is unique for each species. Exemples: 30, 12620, 18810
ScientificName	Description: Name to uniquely identify species. Examples: Buteo buteo, Caldiris alpina
DayNightActive	Description: species activity in circadian cycle. Example: day, day & night, night
VocalActivity	Description: How vocal is the specie Examples: Poor, Average, Good
CallVolume	Description: How loud is the specie Examples: Soft, Average, Loud
nl_breeding	Description: Is the species breeding in The Netherlands? Examples: breeding, non-breeding, both breeding and non breeding individuals
nl_abundance	Description: How abundant is the species in The Netherlands? Examples: rare, scarce, common
nl_MonitoringCoverage	Description: How well is the species monitored in The Netherlands? Examples: Generally absent during survey period, Decent, Good
es_abundance	Description: How abundant is the species in Spain? Examples: rare, scarce, common

es_MonitoringC overage	Description: How well is the species monitored in Spain? Examples: Mediocre, Decent, Good
PECBMS	Description: Is the species part of the Pan-European Common Bird Monitoring Scheme using common birds as indicators. Examples: Yes, No
forest	Description: Is the species usually observed in forests? Examples: Yes, No
heathland	Description: Is the species usually observed in heathland? Examples: Yes, No
marshland	Description: Is the species usually observed in marshlands? Examples: Yes, No
coast	Description: Is the species usually observed on the coast? Examples: Yes, No
city	Description: Is the species usually observed in cities? Examples: Yes, No
farmland	Description: Is the species usually observed in farmlands? Examples: Yes, No

1.4.2 Species filters used in WP2

The detections from *BirdNet 2.4* contain 6522 species. They consist of all the species *BirdNet 2.4* has ever been trained on globally, and do not represent only the European bird populations. These 6522 species constitute the first filter applied to the raw audio recordings.

The second filter is geographic. As detailed in **section 4.2 of the manuscript**, only the species that have been reported in the European Breeding Bird Atlas 2 (EBBA2) to breed within the area covered by TABMON are selected. This corresponds to the 480 species in the TABMON database.

1.4.3 Species selected for WP3

To share the observations from the acoustic network on public data platforms such as GBIF, it is essential to properly validate the BirdNet detections to ensure highly reliable information. To validate the detections, for every single species, we need to calibrate the model output to infer the species presence probability based on the BirdNet confidence score. And to do so, more manual annotations are required, which is not feasible to do for the 480 species within the timeline of TABMON.

For this reason, and to be able to share a subset of the acoustic observations with the best quality possible, we selected ten migratory bird species.

To define the migratory status of the bird species, we used the BIRDBASE classification (https://doi.org/10.1038/s41597-025-05615-3). BIRDBASE is the most comprehensive and

high-quality bird trait database to date and the migratory status data are also used in AVIBASE. We selected the species with yearly, regular, seasonal, and/or long-distance movement (i.e., class Mig 1 in BIRDBASE).

The ten migratory bird species to showcase the TABMON dataset need to be well represented everywhere within the sensor network. Therefore, we followed the steps below to select the ten most common species within the TABMON database. Only the data from 2025 are used here.

1) Calculate the Total, Median, and Average of detections (with confidence > 0.8) for each species across the clusters, and determined how many clusters have more than 100 detections with a confidence > 0.8
2) Sort the table by the Median of detections and select the 10 most common migratory species with BIRDBASE Mig = 1

From this selection, we then select 450 samples per cluster (i.e., 50 per intervals [0, 0.1], [01, 0.2],...,[0.9, 1]) to be manually validated.

The resulting most common 10 migratory species appear to be all Passeriformes. They are shown in **Table S3.2**.

Table S3.2: Common migrant terrestrial bird species selected for sharing on public platforms

Scientific Name	English name		Scientific Name	English Name
Phylloscopus collybita	Common Chiffchaff		Turdus merula	Eurasian Blackbird
Erithacus rubecula	European Robin		Regulus regulus	Goldcrest
Phylloscopus trochilus	Willow Warbler		Prunella modularis	Dunnock
Fringilla coelebs	Common Chaffinch		Troglodytes troglodytes	Eurasian Wren
Emberiza schoeniclus	Common Reed Bunting		Motacilla alba	Pied Wagtail/White Wagtail

In addition to the most common migratory species detected in the TABMON database, we added the species in Table S3.3 which are of specific interest for our local partners.

Table S3.3: Species of interest for local partners with the countries where they are usually observed (ES for Spain, FR for France, NL for The Netherlands, and NO for Norway)

English Name	Scientific Name	Country
Night-active species		
Barn Owl	Tyto alba	FR, ES, NL
Pygmy Owl	Glaucidium passerinum	FR, NO
Little Owl	Athene noctua	ES, FR, NL
Boreal Owl	Aegolius funereus	ES, FR, NO
Scops Owl	Otus scops	ES, FR
Long-eared Owl	Asio otus	ES, FR, NL, NO
Short-eared Owl	Asio flammeus	FR, NL, NO
Tawny Owl	Strix aluco	ES, FR, NL, NO
Eagle Owl	Bubo bubo	ES, FR, NO, NL
European nightjar	Caprimulgus europaeus	ES, FR, NO, NL
Other species		
Little crake	Zapornia parva	NL, FR, ES, NO
Baillon's crake	Zapornia pusilla	ES, FR, NL
Spotted crake	Porzana porzana	ES, FR, NL, NO
Water rail	Rallus aquaticus	ES, FR, NL, NO
Great bittern	Botaurus stellaris	ES, FR, NL, NO
Little bittern	Ixobrychus minutus	ES, FR, NL

2. Country-level strategies

2.1 Norway

<u>Site selection strategy</u>
The Norwegian strategy for the site selection has been conducted in several iterations.

First, the main migration routes and bottlenecks were identified through discussions with the researchers leading the Norwegian Bird Breeding program and involved in the VisAvis project. This led to the selection of relevant areas (clusters) across Norway as shown in **Figure S3.2a**.

Then, local stakeholders from ringing stations, bird observatories (Lista and Utsira), managers of protected areas, and members of Birdlife Norge suggested a list of sites. To harmonize the selection and validate the sites suggested by the local stakeholders, we consulted literature and reports (e.g., *A Birdwatcher's Guide to Norway*, 2024, by Bjørn Olav Tveit), and bird occurrences (Kart | Artsdatabanken). We also searched for protected areas (Miljødirektoratet - Kartkatalog) with mentions of species pre-selected in TABMON (**Table S3.1** and **Table S3.2**). We then visited each cluster to pick the sites that best fit TABMON criteria.

Given the high number of devices for Norway, we added one criteria that consists of having both well monitored sites (ringing station, point-count, regular observation transects) and poorly monitored sites to better assess the complementarity of PAM with established monitoring methods: this explains why we have more than 2-3 sites per cluster (up to 6).
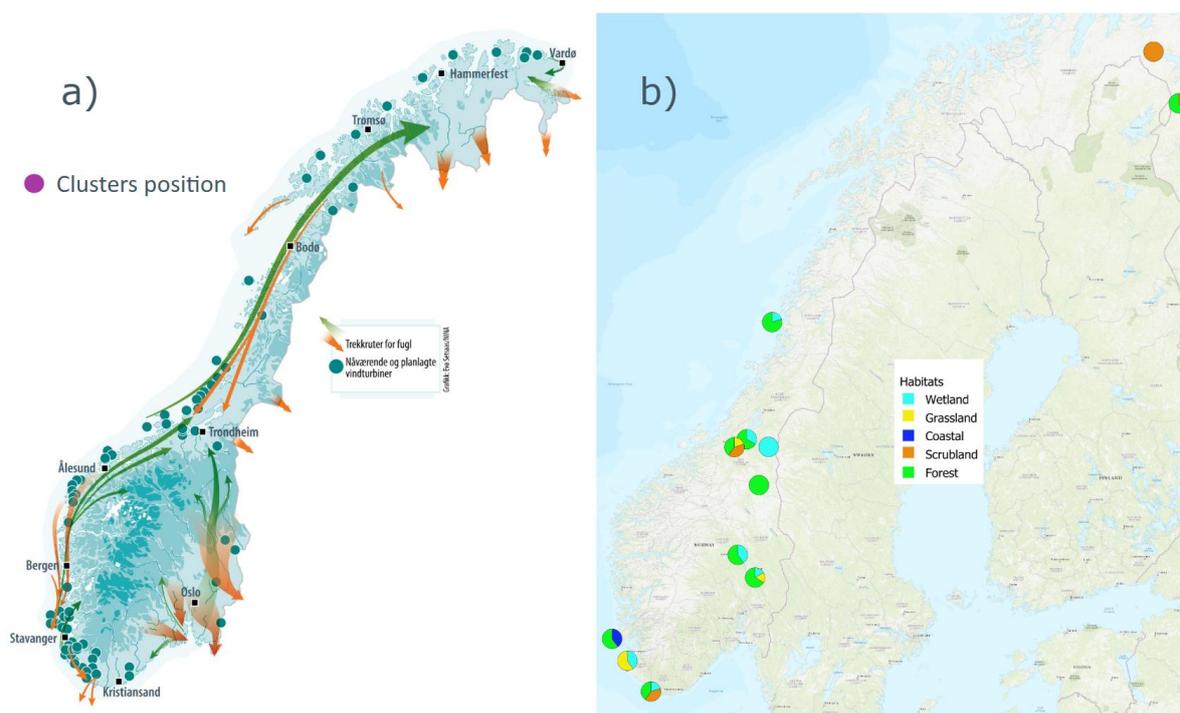
<u>Resulting sites</u>

Figure S3.2: a) TABMON clusters positions based on knowledge about the main migratory flyways from the VisAviS Biodiversa project. b) Habitat proportion in each Norwegian cluster based on the EUNIS habitat classification.
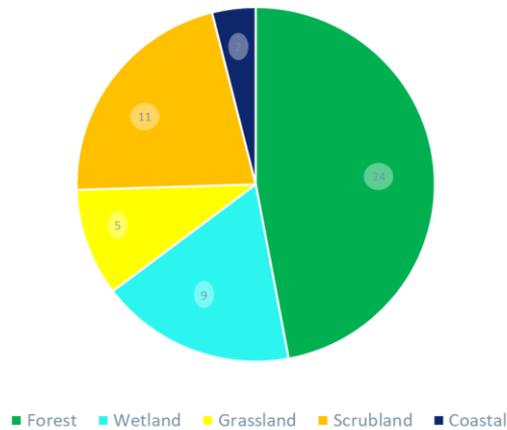

Figure S3.3: Total proportion of the different habitats represented in the Norwegian deployments based on the EUNIS habitat classification.

■ Forest ■ Wetland ■ Grassland ■ Scrubland ■ Coastal

In total, we deployed 51 Buggs in 2025. In at least 90% of the sites, we expect to detect passerine species. In at least 25% of the sites, we expect to detect night-active species.

Overall, half of the sites are in closed habitats and the other half in open habitats (**Figure S3.3**). When possible, we tried to have both open and closed habitats within a cluster (**Figure S3.2b**).

2.2 The Netherlands

Site selection strategy

In the Netherlands, site selection was constrained by the availability of 18 Bugg sensors and limited personnel and maintenance capacity, resulting in a replicated, cluster-based design with a small number of intensively sampled sites. Locations were prioritised where existing collaborations with local stakeholders allowed efficient deployment, maintenance, and permitting. To maximise ecological contrast while maintaining some replication, the design combined within-habitat replication (three wetland sites) with comparisons among habitat types representing common temperate lowland ecosystems in north-western Europe: wetlands, coastal scrubland, and forest. Security considerations were important, as many sites are publicly accessible or host large herbivores; sensors were therefore placed in exclosures or otherwise secure locations where possible. Within clusters, sensors were spaced ≥300 m apart (typically ~0.5–2 km) to minimise overlap in recorded vocalisations. Sensor placement also accounted for environmental constraints such as strong coastal winds and low winter light conditions (e.g. in forests).

Resulting sites

In total, 18 autonomous acoustic sensors were deployed across five spatially separated clusters (**Figure S3.4**), each comprising three to four sensors within a single habitat type.

The sites represent temperate lowland ecosystems in the Netherlands and include three wetlands—Oostvaardersplassen, De Onlanden, and Loenderveen—characterised by reedbeds, shallow water bodies, and strong waterbird soundscapes with seasonal insect activity. A forest cluster was established in Hoge Veluwe, dominated by pine woodland with prominent spring birdsong and relatively low geophony. The coastal cluster in the Amsterdamse Waterleidingduinen represents dune scrubland near the North Sea, characterised by open sandy areas and strong wind-driven geophony. Together, these clusters capture contrasting vegetation structures, hydrological conditions, and soundscape properties while remaining feasible for regular servicing from Amsterdam.

Figure S3.4: Locations of the five study sites (clusters) in the Netherlands. Numbers indicate the number of acoustic sensors deployed within each cluster.

2.3 France

Site selection strategy

In France, all sites have been selected and deployed in National Natural Parks, Regional Natural Parks, and one Nature reserve. We structured the position of the clusters to target places with high bird migration activities and covered by existing monitoring programs. The precise location of the sites was left to the local partners who have field expertise to deploy and maintain the devices. They helped us to obtain deployment permission, and are also interested in the acoustic data produced.

The criteria we gave to the local partners for site selection within a cluster are:

- Passerines migratory stopovers
- Close to existing point counts or other monitoring programs
- Far from human disturbance
- At least 500 meters between two sites
- Good 4G connection (not always possible).

No site has been specifically selected for nocturnal species, yet nocturnal species are present in most of them.

<u>Resulting sites</u>

Three clusters are located in main protected areas in the region around Toulon to facilitate the deployment and maintenance of the sensors. One cluster is located in a migration hotspot halfway between the south of France and The Netherlands in the Forêt d'Orient to optimize the network continuity.
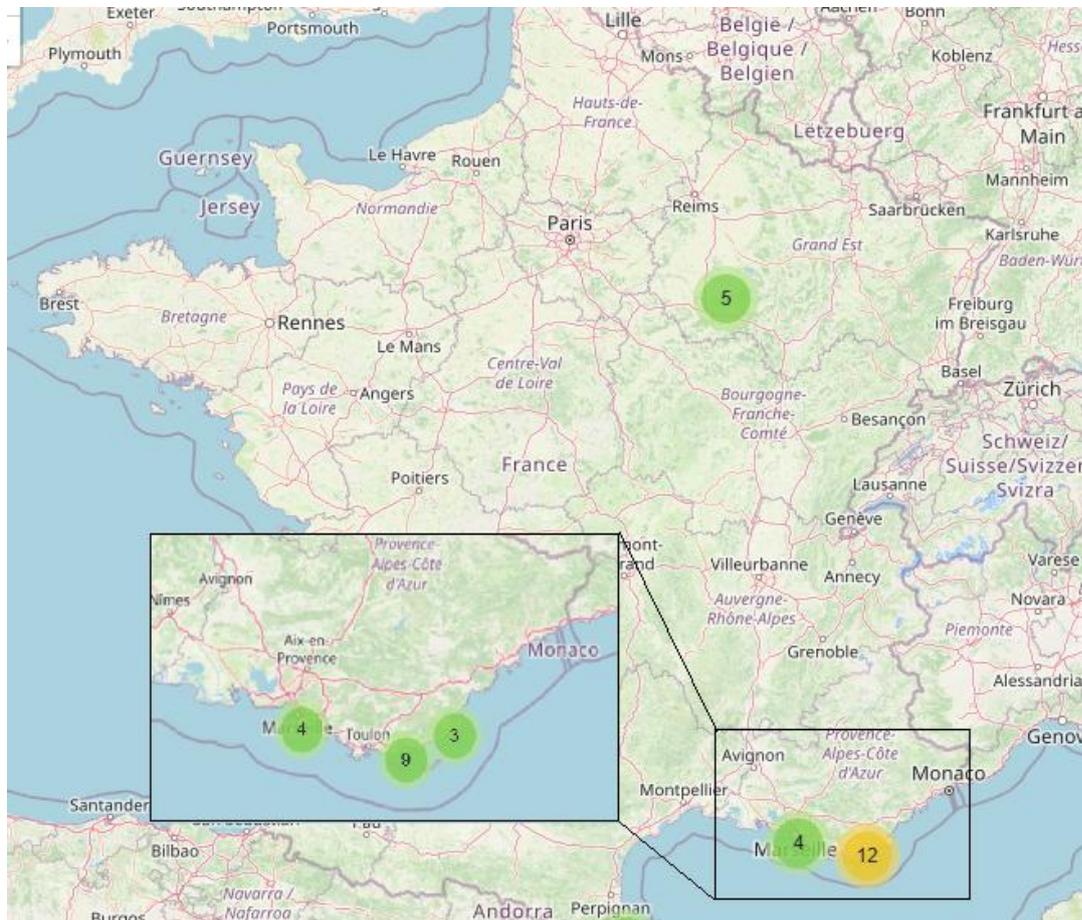
Figure S3.5: Locations of the five study sites in France. Numbers indicate the number of acoustic sensors deployed.

2.4 Spain

<u>Site selection strategy</u>
The sampling strategy in Spain involves a multi-clustered approach, focusing on site selection guidelines, stakeholder collaboration, and diverse habitat representation.

The site selection and deployment follow a collaborative, technically robust workflow designed to ensure optimal field performance:
- Stakeholder Input: Local stakeholders propose between five and six suitable locations per cluster.
- Selection Criteria: The final locations are chosen based on deployment guidelines (such as habitat type and distance), logistical feasibility, security, and alignment with ongoing monitoring programs.
- Pre-deployment BUGG verification: Prior to field installation, each BUGG undergoes technical inspection and functional validation to ensure proper operation and reliable data transmission to the server infrastructure.
- Installation: A minimum of two visits is required per site; the first visit with stakeholders confirms the exact device positioning, while the second focuses on final deployment.

The sampling is stratified across five distinct geographical clusters, targeting nocturnal birds (5 clusters) and migrant passerines (4 clusters).

<u>Resulting sites</u>

Table S3.4: Description of the clusters in Spain

Cluster location	Habitat covered	Target groups
Solsonès	Closed coniferous and riparian forests.	Nocturnal and migratory birds.
Osona	Open farmland and closed deciduous forests; devices often placed on buildings.	Nocturnal birds, specifically high densities of owls.
Mas de Melons	Open semi-arid steppes and non-irrigated cereal farmland.	Migratory and nocturnal birds.
Ebro Delta NP	Open coastal wetlands (marshes, lagoons, reedbeds, and rice fields).	Migratory and nocturnal birds.
Aiguamolls de l'Empordà NP	Open coastal wetlands, including seasonally flooded meadows.	Migratory and nocturnal birds.

Figure S3.6: Locations of the five study sites in Spain. Numbers indicate the number of acoustic sensors deployed.

Supplementary Material S4:
Off-grid power setups per country

The principle is to power the Bugg using a solar panel and a battery. The equipment is mounted in the field and left outdoors for up to two years. It must be robust and capable of withstanding harsh weather conditions. Each country adopted the most suitable solution for the solar panel kit components and the supporting structure.

Caution: Battery choice is critical. Extreme temperatures (>40 °C in Spain and <–20 °C in Norway) significantly reduce battery life. Consult a professional when selecting batteries.

General documentation can be found on the [Bugg website](#).

The following tables list the cost *per device*.

Norway

The solar panel was mounted on a custom aluminium frame and hung on a tree, with the battery box strapped to the same frame.

Table S4.1: Off-grid power setup in Norway

Description	Product	Price (NOK) inc. VAT	Price (€ = 0.086*NOK)) inc. VAT
Solar panel kit	Sparelys.no		
Solar panel	Solcellepanel 55Watt, Sunenergy 67x54cm, mono	955	82
Solar panel cables	Strømkabel 1x6mm², Solarkabel MC4 skjøtekabel, 1m	149	13
Charge controller	EP Solar ViewStar VS1024AU, laderegulator 10A	545	47
Battery cable	Batterikabel med sikringholder, 2x2,5mm², 0,5m, Ringkabelsko	99	9
Fuse	Flatstiftsikring, 15amp, blå	7	0.6
Lithium battery	Lithium Batteri: LiFePo4 12V 24Ah, H, Bluetooth	2145	185
Aluminium frame			
Aluminium profile 25x25x1,5/4m (or 30x30x3 for more robust frame)	Profil Aluminium Vinkel (P-208193) | Byggmax	90	8
Lashing straps 2.5m x2	Smart 365* lastebånd, 2 pk | Obsbygg.no	36	3
Wing nuts x2	304 Stainless Steel Nuts M4 M5 M6 M8 M10 - Temu Norway	6	0.5
Battery box	Batteriboks, 295 x 195 x 245 mm - Biltema.no	119	10
Cable tie x6	Strips 8,7x523, svarte - Biltema.no	9	0.8
Total		**4160 NOK**	**358 €**

VAT rate: 25%

Subscription for one SIM card: Telia 40GB+, 12€ per month.

France

The solar panel was mounted on a custom aluminium frame and hung on a tree, with the battery box held by the same frame.

At sites without suitable trees, an alternative setup was used: a wooden box placed on the ground replaced the aluminium frame.

Table S4.2: Off-grid power setup in France

Description	Product	Price (€) inc. VAT
Solar panel	Mono 50W Black 12V Monocrystalline Solar Panel Photovoltaic Solar Panel	39
Charge controller	EPEVER® 20A Contrôleur de charge solaire MPPT	95
Lithium battery	ECO-WORTHY 12V 30Ah LiFePO4 Rechargeable Lithium Battery	94
Battery box	Iris Ohyama, Airtight Storage Box, 20 L	13
Aluminium frame	Custom-made by a metalworker	150
Straps	2 x 25 mm straps STROXX	17
SD card	SanDisk Ultra microSDXC UHS-I memory card 256 GB+	25
Cable connector	Male/Female Solar Photovoltaic Connector with Solar Cable 4mm²-6mm²	1
Cable	Oududianzi Cable Solaire 6mm2 30m black + 30m red	3.3
Total		**445 €**

VAT rate: 20%

Subscription for one SIM card:

- Orange network: SOSH 100 Go, 9.99€ per month
- SFR network: Lebara 120 to 250 Go, 5.99 to 7.99 € per month

Netherlands

Sensors were strapped to wooden poles (preferably untreated). The battery and cables were stored in a waterproof box placed at the foot of the poles, on the ground.

At sites with reliable network connection, 128 GB SD cards were used; at sites with limited connection, 256 GB SD cards were preferred.

Table S4.3: Off-grid power setup in the Netherlands

Description	Product	Price (€) inc. VAT
Solar panel	Solar panel 60W 12V Mono EnjoySolar, with charge controller and cable	133
Lithium battery	Ecobat AGM Deep Cycle battery 12V 24Ah EDC12-24-2	73
Battery cable		11
Fuse	30A (manually added)	0.48
Battery box	Dribox - IP55 Weatherproof Outdoor Electrical Connection Box	34

Wooden pole	Round chestnut wood garden pole, 12cm diameter, 200cm+ height	15
Straps	Wildlife Monitoring Solutions - Treestraps for trailcameras, 1.8m	5
SD card	Samsung EVO Select MicroSD card, UHS-I U3, 128/256GB	27
Total		**299 €**

SIM card subscription: Oddido.

Spain

Devices were installed either on the ground or on existing structures (e.g., field houses, concrete bases). The battery box was positioned beneath the solar panel, with the charge controller and cables protected inside.

The budget reflects the unit price of each device, including standard installation materials. Additional items (e.g., wooden stakes) were occasionally used but are not included in the budget.

Table S4.4: Off-grid power setup in Spain

Description	Product	Price (€) inc. VAT
Solar panel	Victron energy BlueSolar Monocrystalline solar panel - 12 V - 55 W (SPM040551200), with with MC4 connectors (male & female, 1000V, 4–6 mm², Stäubli)	101.3
Solar panel frame	Solar panel mounting frames with galvanized supports and dark-grey angles, supplied with all essential hardware — screws, washers, studs, clamps, perforated tape, threaded rods, and metal cable glands — ensuring a secure, durable, and field-ready installation	22.1
Lead gel battery	Lead Gel Battery 12V / 33.0Ah Upower UP	86.5
Battery cable	Battery connection cables: single-core, multi-stranded solar cable (4 mm²) in black and red	13.1
Charge controller	PWM Solar Charge Controller (12/24V – 20A), supplied with connection cables, tubular copper terminals, protective fuses, cable glands, and MC4 connectors (male & female) for secure battery and solar panel integration.	58.9
Fuse	Battery-to-Solar Regulator Connection Cables with 30A Fuse	29.0
Battery box	Waterproof Hard Case 350 x 220 x 182 mm	47.8
SD card	SanDisk Extreme PRO 256GB SD card	47.2
Total		**406.0**

Subscription for one SIM card: Vodafone unlimited data, 1.98€ per month through the university contract.

Supplementary Material S5: BirdNET performance assessment

Fig S5.1: Evaluation of BirdNET's false positive rate. We have provided 1,000 BirdNET detections extracted from the French sites to ornithologists who infirmed or confirmed the detections. The figure on the left (validation) shows the validation of the BirdNET detections. Green represents agreement between the ornithologist and BirdNET classification, yellow represents uncertain ground truth (i.e. the ornithologist was not sure about the bird species hears) and red represents mismatch between BirdNET classification and the ornithologist validation. The figure on the right (number of detection in France) shows the total number of detection BirdNET has made per species, the species most detected at the top of the figure and the species the least detected at the bottom of the figure. While BirdNET performance is high on the most frequent species, the performance is underwhelming for the less frequently detected species (i.e. the end of the tail).

Validation — Number of detections in France
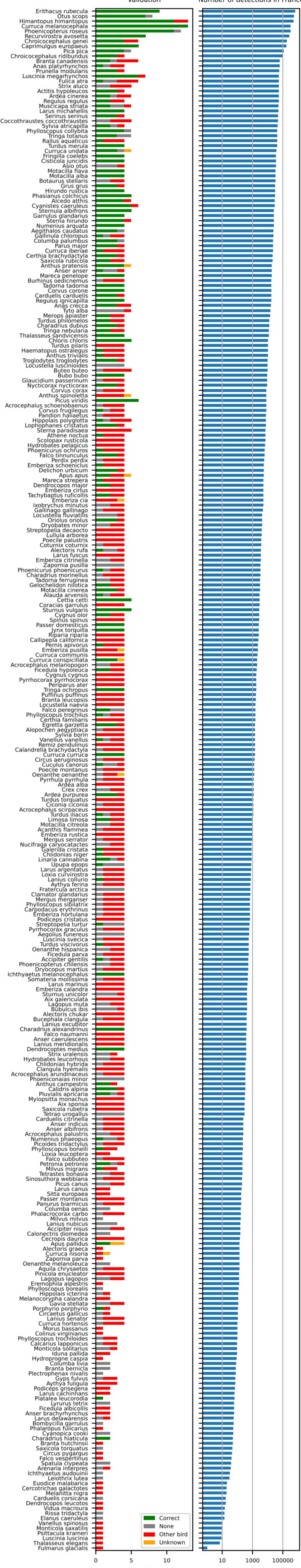
Supplementary Material S6: Carbon footprint of the material

Table S6.1: Carbon footprint for one BUGG and its power supply system.

Description	Emission factor (EF) source	quantity	unit	EF	EF unit	Emissions (kg CO$_2$e)
Bugg device	Nacres PB34 - Acoustic measuring devices	1000	€	0.24	kg CO$_2$e/€	240
Solar panel	Nacres TB11 - Energy : power supply equipment	60	€	0.46	kg CO$_2$e/€	27.6
Charge controller	Nacres TB11 - Energy : power supply equipment	54	€	0.46	kg CO$_2$e/€	24.8
Battery	Nacres TB13 - Energy : batteries and rechargeable battery assemblies	86	€	0.64	kg CO$_2$e/€	55
SD card	Nacres IA23 - Small supplies for external data storage	27	€	0.33	kg CO$_2$e/€	8.9
Battery box + Miscellaneous	Nacres RA23 - Hardware - other miscellaneous workshop supplies	60	€	0.44	kg CO$_2$e/€	26.4
					Total	**382.8**

Table S6.2: Yearly footprint of data transfer, storage and processing per BUGG (438 GB/year).

4G connection (SIM card)	Nacres II02 - Telecom: consumption, subscriptions mobile telephony	100	€	0.16	kg CO2e/€	16
Data transfer (google bucket)	Nacres IA32 - Systems for data storage and backup	43	€	0.33	kg CO2e/€	14.2
Data storage (NIRD)	Nacres IA32 - Systems for data storage and backup	3.6	€	0.33	kg CO2e/€	1.2
Data backup (LIS, UTLN)	Nacres IA32 - Systems for data storage and backup	3.6	€	0.33	kg CO2e/€	1.2
Data processing (LIS, UTLN)	Green Algorithms calculator	230	hGPU	0.021	kg CO2e/ hGPU	4.8
					Yearly total	**37.4**

Carbon footprints of purchases are estimated using the PER1p5[1] database. Goods are classified in categories according to the French system for accountability in research (NACRES) and assigned corresponding monetary emission factors (EFs) expressed in kg CO$_2$e per euro. Item prices are averaged across countries. The EF uncertainties for these categories range from 20 % to 70 %. Carbon footprint of data processing is estimated using the Green Algorithm calculator[2], which provides emissions factors in kg CO$_2$e per GPU-hour. Processing a 5 minute audio file with BirdNET takes approximately 8 sec on a single NVIDIA A100 GPU. All computations are carried out on the LIS cluster in France, where electricity generation is predominantly low-carbon. In countries relying on high-carbon electricity, equivalent computations could emit up to 15 times more CO$_2$e.

[1]ESTEVEZ-TORRES, André; DE PAEPE, Marianne; MARIETTE, Jérôme; JEANNEAU, Laurent; AUMONT, Olivier, 2024, "Purchases emissions in research 1point5 (PER1p5) emission factors", https://doi.org/10.57745/HZNS3S, Recherche Data Gouv, V1
[2]Lannelongue, L., Grealey, J., Inouye, M., Green Algorithms: Quantifying the Carbon Footprint of Computation. Adv. Sci. 2021, 2100707. https://doi.org/10.1002/advs.202100707