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Passive Acoustic Monitoring 2023 Annual Report

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1. Title

Passive Acoustic Monitoring within the Northwest Forest Plan Area: 2023 Annual Report

2. Research Team

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3. Introduction

Northern spotted owl (*Strix occidentalis caurina*) populations have been monitored since the 1990's as part of the Northwest Forest Plan (NWFP) Interagency Monitoring Program to assess effectiveness of the plan, and to inform management and conservation decisions. Population monitoring has revealed continued and increasing rates of population decline throughout the northern spotted owl geographic range, as well as identifying barred owls (*S. varia*) and available habitat as important factors associated with those trends (Lesmeister et al. 2018b, Yackulic et al. 2019, Franklin et al. 2021). Two phases were envisioned in the establishment of the monitoring program (Lint et al. 1999). Phase I of northern spotted owl population monitoring would rely on demographic data and Phase II would be based on habitat monitoring if population change were found to follow trends in forests suitable for nesting and roosting (Lint et al. 1999). The study design for Phase I focused on call-back surveys to locate territorial owls on historical study areas comprised primarily of federal lands, then capturing, marking, and resighting those birds to estimate vital rates and population change (Franklin et al. 1996, Lint et al. 1999). In 2020, the NWFP Regional Interagency Executive Committee decided to discontinue Phase I and transition to Phase II over a two-year period. Phase II entails a

coupling of habitat monitoring with passive acoustic monitoring survey data to assess trends in the populations (Lesmeister et al. 2021, Lesmeister and Jenkins 2022).

Passive acoustic monitoring using autonomous recording units (ARUs) has been demonstrated to be effective for conducting surveys for northern spotted owl and barred owls (Duchac et al. 2020), distinguishing northern spotted owl sex (Dale et al. 2022), estimating pair status (Appel et al. 2023), integrating with traditional territory survey data (Weldy et al. 2023), and detecting trends in northern spotted owl populations (Lesmeister et al. 2021). Further, ARUs allow for extended-duration sessions, which greatly decreases technician effort in the field while increasing the quantity of data collected (Tegeler et al. 2012). Development of artificial intelligence models to automate detections results in rapid and effective data processing and analysis workflows for northern spotted owl and a wide range of other vocal wildlife species (Ruff et al. 2020, Ruff et al. 2021, Ruff et al. 2023).

Here we provide the 2023 annual progress report on passive acoustic monitoring conducted throughout the northern spotted owl range. We report ARU survey effort in randomly selected 5-km^2 hexagons, automated detections of 135 sound classes, and validated results for northern spotted owls, barred owls, and marbled murrelets (*Brachyramphus marmoratus*). Details on previous years' results are available in earlier annual reports (Lesmeister et al. 2018a, Lesmeister et al. 2019, Lesmeister et al. 2022, Lesmeister et al. 2023)

4. Study Area

We collected data within 15 national forests, 5 Bureau of Land Management districts, and 9 National Park lands that were primarily under federal ownership and administered by US Forest Service, US Bureau of Land Management, or National Park Service (Fig. 1). Within the federal lands, we collected data within 10 historical northern spotted owl demographic study areas (Franklin et al. 2021) which were the 20% sampling areas. Nine of the study areas (OLY = Olympic Peninsula, CLE = Cle Elum, RAI = Mount Rainier National Park, COA = Oregon Coast Range, HJA = H.J. Andrews Experimental Forest, TYE = Tyee, KLA = Klamath, CAS = Oregon South Cascades, NWC = Northwest California) were long-term demographic study areas for northern spotted owl monitoring under the Northwest Forest Plan (Franklin et al. 2021), one study area (MAR = Marin County) was included due to long-term and ongoing northern spotted owl demographic monitoring (Fig. 1). The remaining federal lands within the NWFP area were sampled as 2% sampling areas, with additional sampling occurring in some locations (WA 2% = Washington 2% sampled areas; OR 2% = Oregon 2% sampled areas; CA 2% = California 2% sampled areas). In 2023, we collected data from 43 designated Wilderness Areas (Table 1).

5. Methods

Sampling design

We created a uniform layer of 5-km^2 hexagons that covered the entire range of the northern spotted owl (Lesmeister et al. 2021) that is available for download (USFWS 2021). This hexagon size is approximately the size of a northern spotted owl territory core area (Glenn et al. 2004, Schilling et al. 2013) and approximates the home range size reported for barred owls in the Pacific Northwest (Hamer et al. 2007, Singleton et al. 2010, Wiens et al. 2014). Within the

historical demographic study areas, we randomly selected 20% of available hexagons that contained ≥50% forest capable lands and ≥25% federal ownership. Outside the historical demographic study areas, we randomly selected 2% of hexagons throughout the entire NWFP area following the same criteria for forest capable lands and federal ownership, stratified by physiographic province. Forest capable lands were those areas with suitable soil type, plant association, and elevation capable of developing into forest (Davis and Lint 2005). In a subset of our study areas (OLY, COA, KLA), we surveyed non-adjacent hexagons to reduce the probability of detecting the same individual in multiple hexagons. Within each hexagon, we deployed 4 ARUs as our sampling stations (Fig. 2).

We collected acoustic data using Song Meter SM4 (primary device with >95% data collected) and Song Meter Mini (Wildlife Acoustics, Maynard, MA) ARUs that are portable, weatherproof, and easily programmable. The SM4s had two built-in omni-directional microphones with signal-to-noise ratio of 80 decibels (dB) typical at 1 kilohertz (kHz), two SDHC/SDXC flash card slots, average of 543 h of recording battery life, and a recording bandwidth of 0.02–48 kHz at levels of -33.5–122 dB. The Song Meter Mini recorded at the same bandwidth, signal-to-noise ratio of 78 dB, one omni-directional microphone, one SDHC/SDXC flash card slot, and 210–1040 h battery life depending on configuration. These ARU models recorded sound with equivalent sensitivity to normal range of human hearing, and their effective listening radius may be affected by external factors such as terrain, vegetation, and weather events such as wind and rain. At each sampling station within a hexagon, we mounted ARUs to small trees (15–20 cm diameter at breast height) to allow microphones to extend past the bole for unobstructed recording ability. We deployed ARUs on federal land; mid-to-upper slope positions; ≥50 m from roads, trails, and streams to reduce vandalism and excessive noise; spaced ≥500 m apart; and located ≥200 m from edge of the hexagon. We programed ARUs to record from 1 h before sunset to 3 h after sunset, 2 h before sunrise to 2 h after sunrise, and for the first 10 min of every hour throughout the day and night (Fig. 3). The deployment of ARUs and data retrieval were the first two steps in our general workflow for collection, processing, and reporting findings (Fig. 4).

Convolutional neural network (PNW-Cnet) development

Since 2019 we have developed five versions of a convolutional neural network model to automate detections of vocal wildlife species, with each version attaining improved performance and greater number of species identified compared to each preceding version (Fig. 5). Preceding our broadscale passive acoustic monitoring, Duchac et al. (2020) and Duchac et al. (2021) conducted passive acoustic monitoring in 2017 to estimate detection probabilities and occupancy for several owl species in or near three of our study areas (OLY, COA, KLA). From those survey data, Ruff et al. (2020) used the sound clips for six owl species (including northern spotted owl and barred owl) to train our first version of the convolutional neural network (PNW-Cnet v1) to automate species identifications. We replicated and refined the model and process used to train PNW-Cnet v1 for successive PNW-Cnet versions that have been used for data processing. Details on development and performance of PNW-Cnet v1 can be found in Ruff et al. (2020). Briefly, we located target species vocalizations in the 2017 data using the Simple Clustering feature of Kaleidoscope Pro software (version 5.0, Wildlife Acoustics) to generate training data.

Given that convolutional neural network models are designed for image classification, we split all sound files (.wav) into 12 s segments and then converted those to spectrograms, which are image representations of sound (Fig. 6). We used a 12 s interval because it cleanly divides an hour-long field recording and is long enough to fully contain any of the owl calls. To reflect the variation found in field recordings, we generated multiple spectrograms with different parameters for each 12 s clip (Ruff et al. 2020).

The final training dataset used by Ruff et al. (2020) included spectrograms for seven target classes: northern saw-whet owl (*Aegolius acadicus*; *n* = 10,003), great horned owl (*Bubo virginianus*; *n* = 9,999), northern pygmy-owl (*Glaucidium californicum*; *n* = 10,003), western screech-owl (*Megascops kennicottii*; *n* = 10,004), northern spotted owl (*n* = 22,373), barred owl (*n* = 22,204), and noise (*n* = 10,003). We implemented the PNW-Cnet v1 model in Python using Keras, an application programming interface, to Google's TensorFlow software library (Abadi et al. 2015). We trained the PNW-Cnet v1 for 100 epochs on our 94,589 training images, of which 80% were used for training and 20% were set aside as a validation set. See Ruff et al. (2020) for details on model performance for each species.

We found that PNW-Cnet model performance could be improved for target species by increasing the size of the model training dataset and incorporating additional target classes, including vocalizations easily confused with the existing classes. From 2018–2023, we expanded and further developed the PNW-Cnet for processing data with important advancements and expansions occurring each year of the study (Fig. 5). PNW-Cnet v5 includes 135 sound classes, of which are 80 different species, and was trained on 782,918 training images, with about 90% used for training and 10% for validation.

To determine the performance of each version of the PNW-Cnet to correctly classify each sound class, we calculated precision and recall, generated from a test set of clips that were fully tagged by human technicians. Precision is the rate of true positives among apparent detections (clips with an output prediction ≥0.95). Recall is the proportion of calls in the dataset that were detected and correctly identified. To measure class-specific performance for PNW-Cnet v5, we set aside 5% of the intended training dataset (n = 41,202 images), which were fully labeled, and classified these images using the model immediately following training. For each class, we tallied: 1) the number of true positive detections, i.e., clips that contained the class and were assigned a score ≥0.95 for that class; 2) the number of apparent detections, i.e., all clips that were assigned a score ≥0.95 for that class; and 3) the number of available examples, i.e., all clips that contained the class. We calculated precision as true positives divided by apparent detections and recall as true positives divided by available examples.

Data processing

We followed a multi-step workflow that integrated the latest version of PNW-Cnet to efficiently process large volumes of audio data, combining automated identification and human validation (Ruff et al. 2021). This workflow reduced the necessary human effort by >99% compared to full manual review of the data while producing detection/non-detection data based only on human-confirmed detections for chosen classes. PNW-Cnet generates likelihoods (interpretable as probabilities between 0–1) for each sound class for each 12 s clip. We report the number of estimated detections (i.e., number of clips with score exceeding a score threshold) for

each target sound class by study area adjusted by model class precision when available. Generally, precision estimates at the 0.95 threshold were much higher than the recall estimates. As you reduce the review score threshold, recall scores generally increase and precision declines. For example, precision and recall for northern spotted owl four-note calls using the 0.5 threshold vs 0.95 threshold is 0.87 and 0.80, and 0.98 and 0.36, respectively. As we were most concerned with avoiding false positives, we set the threshold high (0.95) to maximize precision over recall for our report summary.

Data validation and sex predictions

Output from PNW-Cnet v5 (used to process 2023 data) was validated through a process of review by trained human technicians (Fig. 4). The human validation process consisted of reviewing 12 s audio clips that met our model prediction threshold. We used the program Kaleidoscope Pro for validating PNW-Cnet output by examining the audio and spectrogram to confirm or correct the model classified sound class. Depending on species-specific objectives and need to generate training data for future versions of the PNW-Cnet, we reviewed sound classes at one of four intensities:

1) Fully review all clips,
2) Confirm species detection/non-detection for each ARU station during each week of survey,
3) Confirm annual detection/non-detection at each ARU station,
4) Confirm annual detection/non-detection at hexagon level (detection on any ARU station within the hexagon).

Prior to 2023, we fully reviewed all PNW-Cnet output that scored at or above 0.25 probability threshold for northern spotted owl location calls. In 2023, we fully reviewed the northern spotted owl location call class ≥0.25 in approximately 12% of hexagons reviewed, then switched to a probability threshold of ≥0.50 once we were confident that we were not affecting occupancy estimates by reducing the threshold for northern spotted owl. We reviewed marbled murrelet and barred owl call classes at a threshold of ≥0.95 to confirm weekly ARU-level occupancy.

All hexagons with <100 northern spotted owl calls classified by the initial validator were reviewed by a second reviewer for confirmation of northern spotted owl presence. High quality spectrograms with confirmed northern spotted owl calls were analyzed to determine aspects of frequency and call length and these values were used to make out-of-sample predictions from a linear model (Dale et al. 2022) to determine the sex of the vocalizing owl. We classified 95% prediction intervals (PI) <0.5 as females and those with 95% PI > 0.5 as male, and predictions not meeting either of these criteria were classified as unknown sex. Hexagons with > 100 northern spotted owl calls or those with evidence of female or pair vocalizations were reviewed again by expert reviewers. Expert reviewers confirmed model predicted female calls and assigned female presence at sites with counter calling, or non-territorial calls overlapping male 4-note hoots. We report the proportion of surveyed hexagons with validated detections for northern spotted owls, marbled murrelets, and barred owls.

Removal of data affected by call-back surveys

Call-back surveys for northern spotted owl and barred owl were commonly used in our study areas by biologists working on other research projects (e.g., Franklin et al. 2021, Wiens et al. 2021) and project-level clearance surveys. These surveys broadcast recorded calls of northern spotted owl, or other target species to elicit a territorial response. Beginning in 2021, we distributed a recording consisting of a brief series of pure tones (1 s at 0.5, 1.5 and 1.0 kHz) for call-back surveyors to voluntarily play at the same volume directly before or after northern spotted owl call-back surveys (USFWS 2021). We requested and received broadcast survey information from surveyors in or around our sampling locations at the end of each field season. We manually validated all ≥0.95 predicted detections of the survey tone from PNW-Cnet v5. We removed any validated detections of the surveyed species if there was a reported or suspected call-back survey in the hexagon on the same night, or if we could identify that the detection was a call-back survey auditorily.

Background noise analysis

Background noise has consistently been found to be an important predictor of detection probabilities in species occurrence models (Duchac et al. 2020, Duchac et al. 2021). Therefore, we used the sound pressure level analysis feature in Kaleidoscope Pro to quantify background noise levels at each ARU sampling station. We created weekly estimates of average daily background noise for each ARU station which are available upon request but not reported here.

6. Results

Here we present the most up to date results that should be considered preliminary with need for further validation and quality-assurance and quality-control before formal analyses can be conducted. The amount of data collected and coverage within the NWFP area has increased each year of passive acoustic monitoring since 2018 (Table 2). In 2023, we surveyed a total of 4,012 sampling stations in 1,009 hexagons (Table 2) with nearly 2.2 million h of recordings (Table 3) and approximately 1 Petabyte of data collected. We conducted surveys in five national parks (Crater Lake, Olympic, North Cascades, Mount Rainier, and Redwood), five Bureau of Land Management districts in Oregon, and 14 national forests (Deschutes, Fremont-Winema, Gifford Pinchot, Klamath, Six Rivers, Mendocino, Mount Baker-Snoqualmie, Mt. Hood, Okanogan-Wenatchee, Olympic, Rogue River-Siskiyou, Shasta-Trinity, Siuslaw, Umpqua, and Willamette). Deployments took place from February 24 – July 27. In 2023, 754 of our sampling stations were in designated Wilderness Areas administered by US National Park Service (n = 391) or US Forest Service (n = 363; Table 1). Each year we experience some degree of data loss by various sources such as wildfire, theft, animal damage, and software or hardware failure. In 2023, barred owl, northern spotted owl and great gray owl (*S. nebulosa*) call-back surveys were reported within or adjacent to our sampled hexagons, and any detections of those species overlapping the night of the audio survey were removed.

PNW-Cnet v5

PNW-Cnet v5 marked a significant increase in the number of species (n = 80) from the

37 in PNW-Cnet v4 (Ruff et al. 2023) and had high precision for most sound classes (Table 4). Using PNW-Cnet v5, we were able to generate predicted detections of all focal and most nontarget species (Table 4). PNW-Cnet v5 precision was high (>0.91) for all northern spotted owl, barred owl, and marbled murrelet call types (Table 4). Precision was also high for anthrophony sounds and other important management species such as corvids (Table 4). We also observed high performance for most of the mammals, but sample size remains low for many of those species (Table 4). Recall was low for many sound classes, which suggests larger training data are needed to improve model performance for recall. There were 24 PNW-Cnet v5 classes that had no apparent detections (spectrograms assigned scores ≥0.95) in the test set or in the 2023 data (Table 4). As precision is defined as the proportion of true positives among apparent detections, it was not possible to estimate precision for these classes at the 0.95 score threshold. These were all new classes whose performance will likely increase with future versions of PNW-Cnet. There were 108 sound classes with precision estimates >0.90 at the 0.95 threshold (recall ranging from 0.01–0.97).

Focal species detections

In 2023, we confirmed ≥1 northern spotted owl detection in all 20% sampling areas and in each of the 2% samples within each state. We consistently found many more male than female detections (Table 5). California study areas (MAR, NWC) had the highest proportion of hexagons with detections (Table 6). Areas in the Washington Cascades (CLE, RAI, WA 2%), Tyee (TYE), and the Oregon Coast Range (COA) had some of the lowest proportion of hexagons with detections (Table 6). The proportion of hexagons with detections has remained consistent on most study areas with multiple years of surveys. TYE is the exception with proportion declining from 0.38 to 0.15 from 2021 to 2023. We did not detect northern spotted owl in Deschutes National Forest, or North Cascades National Park. Indeed, we also did not detect any northern spotted owl north of US Highway 2 in the Washington Cascades (39 hexagons). Northern spotted owl call-broadcast surveys were reported, and we detected the survey tone throughout the study region.

Marbled murrelet keer calls were confirmed in COA, OLY, KLA, RAI, TYE, and 2% areas within the range of murrelet in 2023. Marbled murrelets were commonly detected (91-92% of hexagons) on the two most coastal study areas (COA, OLY) (Table 7). A higher proportion of the Oregon 2% sampled areas had murrelet detections compared to Washington and California (Table 7).

All study areas had high proportions of hexagons with barred owl detections, except MAR and California 2% areas (Table 8). In Washington, we detected barred owls in >90% of surveyed hexagons on the west side of the Cascade Mountains and in CLE on the east side we detected barred owls at 80% of hexagons (Table 8). In the Oregon 20% study areas, we detected barred owls at over 95% of hexagons (Table 8). The greatest amount of barred owl 8-note calls was recorded in COA and the Oregon 2% areas (Table 5). California sites had consistently lower proportion of hexagons and number of barred owl 8-note calls compared to sites in Oregon and Washington (Table 5, Table 8). Mendocino National Forest was the only surveyed federal management unit with no barred owl calls detected. Barred owl call-broadcast surveys occurred in some California sampling areas.

Northern saw-whet owls (*Aegolius acadicus*) and northern pygmy owls (*Glaucidium californicum)* had the greatest number of predicted vocalizations throughout our study area (Table 5). We found >1,000 predicted detections of great gray owls in CAS and the OR 2% area (Table 5). Flammulated owls (*Psiloscops flammeolus*) were most commonly detect in CLE, followed by the 2% sample areas in all three states and NWC (Table 5). Great-horned owl (*Bubo virginianus*) and western screech-owl (*Megascops kennicottii*) calls were predicted in all sampling areas (range: 310–87,970 and 25–212,889, respectively). We found a few potential long-eared owl (*Asio otus*) calls in CAS, CLE, TYE, and CA and OR 2% areas (Table 5).

Northern goshawk (*Accipiter gentilis*), a new sound class in PNW-Cnet v5, were classified at the 0.95 model threshold in all areas, with >8,000 classified in CAS, and the CA and OR 2% areas. Pika (*Ochotona princeps*) were commonly (>5,000) predicted in CAS, CLE, HJA, and WA 2%. Band-tailed pigeon (*Patagioenas fasciata*) call classes were found in all areas with as few as 1,263 in CLE up to 426,194 naïve detections in COA (Table 5). Sooty grouse (*Dendragapus fuliginosus*) call classes were predicted most densely at OLY (1,030,627) and TYE (589,598).

We did not confirm detections for wolves (*Canus lupis*), elk (*Cervus canadensis*), ruffed grouse (Bonasa umbellus), red-tailed hawks (*Buteo jamaicensis*), bald eagles (*Haliaeetus leucocephalus*), osprey (*Pandion haliaetus*), Wilson's warblers (*Cardellina pusilla*), evening grosbeaks (*Hesperiphona vespertina*), orange-crowned warblers (*Leiothlypis celata*), black-headed grosbeaks (*Pheucticus melanocephalus*), chipping sparrows (*Spizella passerine*), pine siskins (*Spinus pinus*), house wrens (*Troglodytes aedon*), or white-crowned sparrows (*Zonotrichia leucophrys*). Each of these species are new classes for PNW-Cnet with small training datasets, so the lack of detections may be from poor model performance rather than absence from areas surveyed. For many of these species the recall in PNW-Cnet v5 may have been too low for any true positives to reach the 0.95 prediction threshold.

7. Discussion

Data collection and processing

Here we report data collected and summaries for passive acoustic monitoring since 2018 within the NWFP area. The first year for full implementation of passive acoustic monitoring of the 2+20% sampling design occurred in 2023 (Lesmeister et al. 2021, Lesmeister and Jenkins 2022). Our goal was to survey approximately 1,100 hexagons which would have included all hexagons that were surveyed in 2022 plus all hexagons included in the full 2% sample outside historical study areas. We were able to survey hexagons surveyed in 2022 and most of the expansion hexagons for a total of 1,009 hexagons surveyed and nearly 2.2 million h of recordings processed and detection encounter histories for 66 species.

With many multi-species survey methods there are tradeoffs that must be made in study design between the number of sampling occasions and sites surveyed (Sanderlin et al. 2014). We have demonstrated the ability to resolve many of these tradeoffs by using passive acoustic monitoring with long-duration deployments, random site selection, multiscale clustered sampling, and high-throughput data processing for a wide range of species over large geographic regions. The NWFP passive acoustic monitoring program was designed to ensure effectiveness

for tracking trends in northern spotted owl populations (Lesmeister et al. 2021), but by using a random selection of 5-km^2 hexagons with multiple sampling stations, we have a design suitable for detecting and studying many other forest-adapted wildlife species (Tosa et al. 2021, Lesmeister and Jenkins 2022). For example, Rugg et al. (2023) used data collected in 2021 and PNW-Cnet output to evaluate western screech-owl occupancy and the effect of barred owls. Using our data from two study areas, Duarte et al. (2024) demonstrated that the combination of passive acoustic monitoring and PNW-Cnet are effective to estimate marbled murrelet intensity of use across broad scales and will significantly enhance long-term population monitoring. Using a subset of our passive acoustic monitoring data, Weldy et al. (2024) annotated dawn chorus recordings for an open-access dataset that is a valuable resource for researchers developing automated identification tools and those studying the relationship of dawn chorus species to the forest environment.

We continue to develop and improve PNW-Cnet as demonstrated by our use of the most recent version to process data collected in 2023. PNW-Cnet v5 is in preparation for publication and will include performance metrics reported here and an easy to install tool that can be used by field biologists to process passive acoustic monitoring data on personal computers. With continued development of PNW-Cnet we anticipate an expansion of its use for many additional applications to address pressing ecological and conservation challenges.

The primary challenges for the 2023 data collection season were field staff hiring constraints, early season (March–April) weather with low-elevation snow, wildfires in August, and general challenges associated with expanding work into areas unfamiliar to field crews. We continue to gain experience with accessing survey sites and seek continual improvement and efficiencies with recently hired permanent fulltime staff in support of the monitoring program. Once the data are collected, the most significant constraint to producing occupancy estimates for northern spotted owl continues to be our ability to identify calls originating from human surveyors using broadcast play-back surveys. Broadcast surveys have been the primary method of determining northern spotted owl occupancy for the last 40 years and are widely used by private, state, tribal, and federal entities. The use of a three-note tone (USFWS 2021) by some northern spotted owl call-back surveyors has greatly enhanced our ability to screen out and identify call-back surveys during data processing with human review and should expedite occupancy estimates for those overlapping survey areas.

In 2023, we expanded the monitoring network through state and federal partnerships. For example, we partnered with Washington Department of Natural Resources and the Mount Baker-Snoqualmie National Forest to conduct passive acoustic monitoring surveys on that forest. We partnered with California Department of Parks and Recreation to design a survey plan and process data from three hexagons on their lands that they surveyed. We continue to actively seek partnerships to expand the monitoring network with no additional cost to the program. Additionally, data processing tools developed by the program are freely available and we (PNW Bioacoustics Lab) host workshops each fall to train federal biologists to use the tools for project-level surveys. The 30-year NWFP meta-analysis of northern spotted owl populations is in progress and will include the final analyses of demography and the transition to occupancy. It will include 2023 data to produce the first estimates of range-wide occupancy and population for

northern spotted owls.

Northern spotted owl

Generally, the naïve occupancy of northern spotted owl increased from north to south. We found northern spotted owls in 17%, 24%, and 51% of WA, OR, and CA hexagons respectively. We detected no northern spotted owls north of Highway 2 in the Washington Cascades sampling area, where 35 of 39 surveyed hexagons had barred owl calling. This may be evidence of extirpation from a region which has had the longest exposure to barred owls, however, more years of monitoring data will be needed. Encouragingly, we have not observed a dramatic decline in naïve occupancy rates in most study areas where we now have several years of passive acoustic monitoring. The TYE study area is the exception, where we have conducted three years of passive acoustic monitoring and observed a decline in the proportion of hexagons with detections from 0.38 to 0.15 between 2021 and 2023. A detailed analysis is warranted to investigate potential causes of this change in naïve occupancy rate. We used a combination of a linear predictive model (Dale et al. 2022) and expert review to determine sex of northern spotted owl detections. We confirmed 31,326 four-note calls recorded in 2023. Most of those calls were classified as unknown sex (n = 26,582), but in spot review we found that most of the unknown calls are likely males. Confirmed female four-note calls (n = 755) were only 2.4% of all confirmed four-note calls, highlighting that males are far more vocal and, therefore, more detectable than females. This difference in detection of males and females has important implications for interpreting survey results to predict pair status (Appel et al. 2023). A six-week survey of a hexagon that results in only a single confirmed male detection has a 0.47 probability of being a pair but the female was not detected (Appel et al. 2023).

Marbled murrelet

Naïve occupancy rates of marbled murrelets in the COA and OLY study areas have remained mostly consistent since 2018, and RAI since 2021. The data collected in 2023 provide us with the first broader occupancy rates outside these study areas, but our estimates include areas surveyed outside the expected range of marbled murrelets inland. In future years we will report naïve occupancy rates only for those areas within the expected range.

Barred owl

Barred owls have been spreading southwards from Canada for the last 40-50 years and are one of the most detected species in our surveys. We observed detections of barred owls in 89% of hexagons in Washington, 93% in Oregon, and 46% of hexagons in California. We detected barred owls in only one of seven hexagons surveyed in MAR study area and in zero of the 13 hexagons surveyed on the Mendocino National Forest. We observed a general pattern of areas with the highest barred owl naïve occupancy rates having the lowest northern spotted owl naïve occupancy rates (Tables 6, 7).

Biodiversity

We are increasingly confident that the coupling of passive acoustic monitoring with PNW-Cnet provides the foundation for a powerful toolbox for tracking changes and the drivers

of northern spotted owl population change. Further, we are now collecting valuable data for many other wildlife species and are working to identify winners and losers in dynamic landscapes (see Rugg et al. 2023). These opportunities would not be possible with a monitoring program based in traditional field methods that are single-species focused (Lesmeister and Jenkins 2022). We have clearly expanded the number of species we can provide useful information to evaluate population trends and landscape associations, but the monitoring design will not be suitable for all species. Therefore, additional study is needed to resolve which additional species or communities can be integrated into the standardized flow of information generated by the monitoring program. The list of species to be included will be limited to the taxa appropriate to the spatial and temporal (i.e., the target species is forest-adapted and the breeding season range overlaps the NWFP area) sampling design and the pool of species that can be included in automated systems.

We also have several human disturbance noise classes in PNW-Cnet v5 (Table 4). These anthrophony noise classes can provide information on landscape context of our sampling areas. For example, the Oregon study areas, COA, KLA, TYE, and the 2% OR landscape have far more naïve logging yarding system whistle (i.e., yarder' machine) detections (>50,000) compared to other regions (<7,000). These data will be increasingly informative with long-term monitoring to quantify occupancy dynamics in relation to these disturbance indicators. We will likely be able to generate new insights into these ecosystems due to the flexibility and scale of the biodiversity monitoring program.

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10. Tables

Table 1. The number of autonomous recording unit stations surveyed during 2023 in 43 designated Wilderness Areas administered by US Forest Service or US National Park Service.

Wilderness Area	Stations surveyed
US Forest Service	
Alpine Lakes	27
Boulder Creek	1
Buckhorn	9
Bull of the Woods	3
Clackamas	2
Clearwater	2
Colonel Bob	8
Cummins Creek	3
Devil's Staircase	20
Diamond Peak	8
Drift Creek	2
Glacier Peak	8
Goat Rocks	8
Indian Heaven	2
Lake Chelan-Sawtooth	4
Mark O. Hatfield	4
Menagerie	4
Mount Hood	9
Mount Jefferson	17
Mount Skokomish	4
Mount Washington	2
Mountain Lakes	10
Noisy-Diobsud	4
North Fork	1
Opal Creek	10
Pasayten	4
Red Buttes	4
Rock Creek	1
Rogue-Umpqua Divide	10
Salmon-Huckleberry	1
Siskiyou	1
Sky Lakes	63
Snow Mountain	4

The Brothers	4
Three Sisters	49
Trinity Alps	15
William O. Douglas	23
Yolla Bolly-Middle Eel	8
Yuki	4
US National Park Service	
Mount Rainier	124
Olympic	238
Phillip Burton	7
Stephen Mather	22
TOTAL	754

Table 2. Passive acoustic monitoring effort during 2018–2023 within in the Northwest Forest Plan Area, summarized by historical study area (i.e., 20% sampling) and 2% sampling (outside 20% sample density) by state. COA = Oregon Coast Range, OLY = Olympic Peninsula, KLA = Klamath, CLE = Cle Elum, TYE = Tyee, HJA = H.J. Andrews Experimental Forest, CAS = Oregon South Cascades, NWC = Northwest California, MAR = Marin County, RAI = Mount Rainier National Park.

Area	Number of hexagons						Number of stations					
	2018[a]	2019	2020	2021	2022	2023	2018[a]	2019	2020	2021	2022	2023
COA	120	106	120	120	117	120	578	413	471	475	466	476
OLY	88	120	119	119	120	120	436	472	464	472	474	479
KLA		63	73	73	73	73		244	290	276	292	292
CLE			69	75	75	75			267	298	299	300
TYE				40	40	40				155	160	160
HJA				70	70	70				279	280	278
CAS				98	98	98				380	391	391
NWC				30	30	30				120	119	118
MAR				7	7	7				26	27	27
RAI				11	24	24				43	96	96
WA 2%[b]					23	79					91	312
OR 2%[b]					13	166					52	661
CA 2%						76						299
TOTAL	208	289	381	643	690	1,009	1,014	1,129	1,492	2,524	2,747	4,012

[a] During 2018 survey design was five stations per hexagon.

[b] In 2022, Gifford Pinchot National Forest in Washington and Umpqua National Forest in Oregon were sampled at 2%.

Table 3. Thousands of hours of passive acoustic monitoring data collected during 2018–2023 in each study area and processed for automated species identification with PNW-Cnet. COA = Oregon Coast Range, OLY = Olympic Peninsula, KLA = Klamath, CLE = Cle Elum, TYE = Tyee, HJA = H.J. Andrews Experimental Forest, CAS = Oregon South Cascades, NWC = Northwest California, MAR = Marin County, RAI = Mount Rainier National Park. WA 2%, OR 2%, and CA 2% were data collected in each state on the 2% sampling outside the 20% sampling density on historical study areas.

Study area	2018[a]	2019	2020	2021	2022	2023
COA	197	155	187	217	258	259
OLY	147	184	219	215	264	271
KLA		92	130	135	162	171
CLE			104	153	152	168
TYE				78	92	88
HJA				131	150	149
CAS				178	188	195
NWC				48	54	62
MAR				11	10	15
RAI				11	51	71
WA 2%[b]					44	192
OR 2%[b]					30	385
CA 2%						151
TOTAL	344	431	640	1,177	1,456	2,179

[a] During 2018 survey design was five stations per hexagon.

[b] In 2022, Gifford Pinchot National Forest in Washington and Umpqua National Forest in Oregon were sampled at 2%.

Table 4. Precision and recall estimates for each sound class of the convolutional neural network (PNW-Cnet v5) used to process bioacoustics data collected during 2023. Unless noted for spotted owl location call, estimates are based on a prediction threshold of 0.95 and were generated with a test set of 41,202 spectrogram images. Estimates for the classes with no apparent detections (images assigned scores ≥ 0.95) in the test set or in the 2023 data are denoted as NA.

Class	Sound	Species	Category	Test images	Precision	Recall
STOC_4Note	Spotted owl four-note location call	*Strix occidentalis*	Owls	1,905	0.981	0.361
STOC_Series	Spotted owl series call	*Strix occidentalis*	Owls	632	0.987	0.369
Strix_Bark	Strix owl bark	*Strix spp.*	Owls	227	0.911	0.498
Strix_Whistle	Strix owl contact whistle	*Strix spp.*	Owls	306	0.987	0.507
STVA_8Note	Barred owl eight-note call	*Strix varia*	Owls	1,245	0.983	0.475
STVA_Insp	Barred owl inspection call	*Strix varia*	Owls	906	0.987	0.681
STVA_Series	Barred owl series call	*Strix varia*	Owls	887	0.995	0.240
BRMA1	Marbled murrelet keer call	*Brachyramphus marmoratus*	Other birds	1,188	0.991	0.926
Airplane	Airplane	NA	Anthrophony	453	0.909	0.022
Chainsaw	Chainsaw	NA	Anthrophony	242	0.964	0.223
Growler	Military jet	NA	Anthrophony	57	1.000	0.228
Gunshot	Gunshot	NA	Anthrophony	318	0.994	0.550
Highway	Highway noise	NA	Anthrophony	253	1.000	0.012

Class	Sound	Species	Category	Test images	Precision	Recall
Horn	Car horn	NA	Anthrophony	32	NA	NA
Human	Human speech	NA	Anthrophony	490	1.000	0.174
Survey_Tone	Spotted owl survey tone	NA	Anthrophony	501	1.000	0.974
Train	Train	NA	Anthrophony	138	0.980	0.355
Yarder	Yarder (machine)	NA	Anthrophony	345	0.961	0.499
COBR1	American crow	*Corvus brachyrhyncos*	Corvids	155	0.972	0.226
COCO1	Common raven	*Corvus corax*	Corvids	1,272	0.992	0.378
CYST1	Steller's jay	*Cyanocitta stelleri*	Corvids	1,331	0.982	0.364
CYST2	Steller's jay	*Cyanocitta stelleri*	Corvids	18	NA	NA
NUCO1	Clark's nutcracker	*Nucifraga columbiana*	Corvids	242	1.000	0.475
PECA1	Canada jay	*Perisoreus canadensis*	Corvids	943	0.977	0.670
Bullfrog	Bullfrog	NA	Environmental sound	82	1.000	0.402
Chicken	Chicken	NA	Environmental sound	220	1.000	0.114
Cow	Cow	NA	Environmental sound	221	1.000	0.032
Creek	Stream noise	NA	Environmental sound	465	0.992	0.538
Cricket	Cricket	NA	Environmental sound	2,488	0.995	0.947

Class	Sound	Species	Category	Test images	Precision	Recall
Dog	Dog	NA	Environmental sound	1,078	0.987	0.277
Fly	Buzzing insect	NA	Environmental sound	1,968	0.986	0.355
Frog	Frog chorus	NA	Environmental sound	746	0.987	0.617
Rain	Rain	NA	Environmental sound	3,700	0.991	0.213
Thunder	Thunder	NA	Environmental sound	73	1.000	0.288
Tree	Tree creaking	NA	Environmental sound	816	0.960	0.378
CALA1	Coyote	*Canis latrans*	Mammals	70	1.000	0.086
CALU1	Wolf howl	*Canis lupus*	Mammals	92	1.000	0.337
CECA1	Elk	*Cervus canadensis*	Mammals	28	NA	NA
OCPR1	American pika	*Ochotona princeps*	Mammals	275	1.000	0.636
ODOC1	Deer snort	*Odocoileus spp.*	Mammals	20	1.000	0.050
TADO1	Douglas squirrel rattle	*Tamiasciurus douglasii*	Mammals	767	0.966	0.785
TADO2	Douglas squirrel chirp	*Tamiasciurus douglasii*	Mammals	726	0.986	0.667
TAMI1	Chipmunk spp. chirp	*Neotamias spp.*	Mammals	1,075	0.985	0.797
URAM1	Black bear juvenile	*Ursus americanus*	Mammals	37	1.000	0.405
Wildcat	Wildcat scream	Felid	Mammals	25	1.000	0.120

Class	Sound	Species	Category	Test images	Precision	Recall
ANCA1	Sandhill crane	*Antigone canadensis*	Other birds	42	1.000	0.048
BOUM1	Ruffed grouse	*Bonasa umbellus*	Other birds	60	NA	NA
BRCA1	Canada goose	*Branta canadensis*	Other birds	400	0.992	0.303
BRMA2	Marbled murrelet (other calls)	*Brachyramphus marmoratus*	Other birds	56	NA	NA
CACA1	California quail	*Callipepla californica*	Other birds	117	0.941	0.410
CHMI1	Common nighthawk "peent"	*Chordeiles minor*	Other birds	686	0.980	0.723
CHMI2	Common nighthawk "boom"	*Chordeiles minor*	Other birds	495	0.986	0.844
DEFU1	Sooty grouse	*Dendragapus fuliginosus*	Other birds	817	0.983	0.502
DEFU2	Sooty grouse	*Dendragapus fuliginosus*	Other birds	56	1.000	0.232
GADE1	Wilson's snipe	*Gallinago delicata*	Other birds	52	1.000	0.173
MEGA1	Wild turkey	*Meleagris gallapavo*	Other birds	134	1.000	0.052
ORPI1	Mountain quail	*Oreortyx pictus*	Other birds	584	1.000	0.377
ORPI2	Mountain quail	*Oreortyx pictus*	Other birds	70	1.000	0.286
PAFA1	Band-tailed pigeon	*Patagioenas fasciata*	Other birds	669	0.990	0.718

Class	Sound	Species	Category	Test images	Precision	Recall
PAFA2	Band-tailed pigeon	*Patagioenas fasciata*	Other birds	74	1.000	0.108
PHNU1	Common poorwill	*Phalaenoptilus nuttallii*	Other birds	477	0.993	0.841
STDE1	Eurasian collared dove	*Streptopelia decaocto*	Other birds	52	1.000	0.058
ZEMA1	Mourning dove	*Zenaida macrourus*	Other birds	338	0.994	0.465
AEAC1	Northern saw-whet owl	*Aegolius acadicus*	Owls	595	0.963	0.872
AEAC2	Northern saw-whet owl	*Aegolius acadicus*	Owls	10	NA	NA
ASOT1	Long-eared owl	*Asio otus*	Owls	29	1.000	0.035
BUVI1	Great horned owl song	*Bubo virginianus*	Owls	781	0.996	0.604
BUVI2	Great horned owl calls	*Bubo virginianus*	Owls	236	0.987	0.314
GLGN1	Northern pygmy-owl	*Glaucidium califonicum*	Owls	1,179	0.956	0.774
MEKE1	Western screech-owl trill	*Megascops kennicottii*	Owls	837	0.993	0.666
MEKE2	Western screech-owl bark	*Megascops kennicottii*	Owls	138	1.000	0.022
MEKE3	Western screech-owl juvenile	*Megascops kennicottii*	Owls	254	0.989	0.677
PSFL1	Flammulated owl	*Psiloscops flammeolus*	Owls	1,052	0.998	0.873
STNE1	Great gray owl	*Strix nebulosa*	Owls	139	1.000	0.648

Class	Sound	Species	Category	Test images	Precision	Recall
STNE2	Great grey owl	*Strix nebulosa*	Owls	32	1.000	0.031
ACCO1	Cooper's hawk series call	*Accipiter cooperii*	Raptors	18	1.000	0.389
ACGE1	Northern goshawk series call	*Accipiter gentilis*	Raptors	273	0.990	0.725
ACGE2	Northern goshawk scream	*Accipiter gentilis*	Raptors	284	0.990	0.673
ACST1	Sharp-shinned hawk series call	*Accipiter striatus*	Raptors	26	1.000	0.346
BUJA1	Red-tailed hawk scream	*Buteo jamaicensis*	Raptors	64	NA	NA
BUJA2	Red-tailed hawk other call	*Buteo jamaicensis*	Raptors	25	NA	NA
FACO1	Merlin	*Falco columbarius*	Raptors	27	1.000	0.667
FASP1	American kestrel	*Falco sparverius*	Raptors	31	1.000	0.516
HALE1	Bald eagle	*Haliaeetus leucocephalus*	Raptors	24	NA	NA
PAHA1	Osprey	*Pandion haliaetus*	Raptors	67	NA	NA
Raptor	Raptor scream call	*Accipitrid*	Raptors	183	1.000	0.087
CAGU1	Hermit thrush	*Catharus guttatus*	Songbirds	1,413	0.995	0.297
CAGU2	Hermit thrush	*Catharus guttatus*	Songbirds	40	1.000	0.025
CAGU3	Hermit thrush	*Catharus guttatus*	Songbirds	283	0.824	0.099

Class	Sound	Species	Category	Test images	Precision	Recall
CAPU1	Wilson's warbler	*Cardellina pusilla*	Songbirds	20	NA	NA
CAUS1	Swainson's thrush	*Catharus ustulatus*	Songbirds	944	0.985	0.405
CAUS2	Swainson's thrush	*Catharus ustulatus*	Songbirds	330	0.977	0.388
CCOO1	Olive-sided flycatcher	*Contopus cooperi*	Songbirds	778	0.978	0.794
CCOO2	Olive-sided flycatcher	*Contopus cooperi*	Songbirds	286	0.988	0.594
CHFA1	Wrentit	*Chamaea fasciata*	Songbirds	421	0.995	0.435
COSO1	Western wood-pewee	*Contopus sordidulus*	Songbirds	261	0.975	0.295
EMDI1	Pacific-slope flycatcher	*Empidonax difficilis*	Songbirds	135	NA	NA
EMOB1	Dusky flycatcher	*Empidonax oberholseri*	Songbirds	279	0.984	0.860
HAPU1	Purple finch	*Haemorhous purpureus*	Songbirds	85	1.000	0.341
HEVE1	Evening grosbeak	*Hesperiphona vespertina*	Songbirds	27	NA	NA
IXNA1	Varied thrush	*Ixoreus naevius*	Songbirds	1,719	0.970	0.189
IXNA2	Varied thrush	*Ixoreus naevius*	Songbirds	146	0.935	0.493
JUHY1	Dark-eyed junco	*Junco hyemalis*	Songbirds	289	0.951	0.471
LECE1	Orange-crowned warbler	*Leiothlypis celata*	Songbirds	69	NA	NA

Class	Sound	Species	Category	Test images	Precision	Recall
LOCU1	Red crossbill	*Loxia curvirostra*	Songbirds	58	0.833	0.086
MYTO1	Townsend's solitaire	*Myadestes townsendi*	Songbirds	718	0.988	0.905
PHME1	Black-headed grosbeak	*Pheucticus melanocephalus*	Songbirds	156	NA	NA
PILU1	Western tanager song	*Piranga ludoviciana*	Songbirds	230	NA	NA
PILU2	Western tanager call	*Piranga ludoviciana*	Songbirds	176	0.667	0.011
PIMA1	Spotted towhee song	*Pipilo maculatus*	Songbirds	176	NA	NA
PIMA2	Spotted towhee call	*Pipilo maculatus*	Songbirds	351	0.987	0.664
POEC1	Chickadee song	*Poecile spp.*	Songbirds	416	0.986	0.514
POEC2	Chickadee call	*Poecile spp.*	Songbirds	257	1.000	0.035
SICU1	Mountain bluebird	*Sialia currucoides*	Songbirds	24	1.000	0.667
SITT1	Nuthatch spp	*Sitta spp.*	Songbirds	1,680	0.992	0.441
SITT2	Nuthatch spp	*Sitta spp.*	Songbirds	61	1.000	0.541
SPPA1	Chipping sparrow	*Spizella passerina*	Songbirds	29	NA	NA
SPPI1	Pine siskin	*Spinus pinus*	Songbirds	82	NA	NA
TRAE1	House wren	*Troglodytes aedon*	Songbirds	25	NA	NA

Class	Sound	Species	Category	Test images	Precision	Recall
TUMI1	American robin whinny	*Turdus migratorius*	Songbirds	583	0.961	0.295
TUMI2	American robin other calls	*Turdus migratorius*	Songbirds	488	0.962	0.051
VIHU1	Hutton's vireo	*Vireo huttoni*	Songbirds	57	1.000	0.035
ZOLE1	White-crowned sparrow	*Zonotrichia leucophrys*	Songbirds	31	NA	NA
COAU1	Northern flicker series call	*Colaptes auratus*	Woodpeckers	833	0.996	0.558
COAU2	Northern flicker "skew"	*Colaptes auratus*	Woodpeckers	264	1.000	0.239
DRPU1	Downy woodpecker	*Dryobates pubescens*	Woodpeckers	275	1.000	0.720
Drum	Non-sapsucker drum	*Picid*	Woodpeckers	700	0.963	0.376
HYPI1	Pileated woodpecker	*Dryocopus pileatus*	Woodpeckers	634	0.994	0.719
LEAL1	White-headed woodpecker	*Leuconotopicus albolarvatus*	Woodpeckers	277	0.982	0.191
LEVI1	Hairy woodpecker	*Leuconotopicus villosus*	Woodpeckers	135	1.000	0.089
LEVI2	Hairy woodpecker	*Leuconotopicus villosus*	Woodpeckers	19	NA	NA
MEFO1	Acorn woodpecker	*Melanerpes formicivorus*	Woodpeckers	112	1.000	0.036
SPHY1	Sapsucker spp drum	*Sphyrapicus spp.*	Woodpeckers	268	1.000	0.078
SPHY2	Sapsucker spp call	*Sphyrapicus spp.*	Woodpeckers	37	NA	NA

Class	Sound	Species	Category	Test images	Precision	Recall
SPTH1	Williamson's sapsucker drum	*Sphyrapicus thyroideus*	Woodpeckers	32	NA	NA

Table 5. Estimated number of detections of PNW-Cnet v5 sound classes from passive acoustic monitoring data by study area collected in 2023. Estimated detections for each sound class were calculated as the number of 12 s clips in the audio dataset to which the PNW-Cnet v5 assigned a score exceeding 0.95 for that class, multiplied by the precision estimate (Table 4). Validated call counts are given for the primary northern spotted owl (NSO) and survey tone call classes which were fully reviewed at the 0.5 threshold. CAS = Southwest Cascades, OR; CLE = Cle Elum, WA; COA = Coast Range, OR; HJA = H.J. Andrews Experimental Forest, OR; KLA = Klamath Range, OR; NWC = Northwest California, CA; OLY = Olympic Peninsula, WA; RAI = Mount Rainier, WA; TYE = Tyee, OR; WA 2%= 2% random sample of federal lands in Washington; OR 2 = 2% random sample of federal lands in Oregon; CA 2= 2% random sample of federal lands in California. See Table 4 for species and class codes.

Sound	CAS	CLE	COA	HJA	KLA	MAR	NWC	OLY	RAI	TYE	CA 2%	OR 2%	WA 2%
NSO female 4-note[a]	6	0	24	30	259	215	137	2	0	0	44	38	0
NSO male 4-note[a]	330	114	1	437	396	118	1,200	137	9	10	551	685	1
NSO Unk sex 4-note[a]	1,914	1,186	317	1,878	1,775	9,992	2,811	1,952	94	37	2,525	2,046	55
NSO series[a]	240	43	6	497	354	5,746	377	298	0	20	609	4,876	1,907
Strix owl contact whistle	884	457	1,794	1,021	4,137	3,054	394	2,132	213	692	609	4,876	1,907
NSO bark	321	16	20	158	202	560	318	97	0	0	426	123	4
Survey tone[a]	104	20	69	11	137	0	6	0	0	24	7	147	10
Barred owl 8-note	12,862	14,112	61,058	25,093	19,875	17	3,013	27,357	10,810	19,169	3,278	56,641	17,119
Barred owl inspection	15,046	10,855	40,797	14,241	16,543	149	2,709	12,981	6,744	15,080	2,894	45,714	10,871
Barred owl series	2293	1564	12,871	4,668	4,861	5	423	3,678	1,262	4,268	367	9,388	1,811

Sound	CAS	CLE	COA	HJA	KLA	MAR	NWC	OLY	RAI	TYE	CA 2%	OR 2%	WA 2%
Marbled murrelet keer	330	415	63,971	333	292	85	200	54,537	3,096	294	12,765	16,165	1,665
Airplane	9	62	27	16	30	16	7	40	0	5	24	314	88
Chainsaw	299	1,578	8,787	675	6,530	69	1,090	2,859	151	2,275	3,186	9,159	1,651
Military jet	31	73	48	877	4	0	2,841	28	0	4	39,908	1,829	49
Gunshot	587	1,969	3,260	360	819	7	236	4,765	697	1,046	220	7,978	4,652
Highway noise	1,108	2,032	82	122	4,289	2	3	1,701	6	11	152	2,091	274
Human speech	1,135	645	1,578	548	442	367	217	687	469	363	1,250	3,292	2,101
Train	12	750	649	1	2,978	2	1	13	0	43	2,152	2,372	765
Yarder	717	42	69,797	7,406	59,405	38	19	5,356	128	29,467	893	54,796	1,362
American crow	140	260	294	112	888	485	177	762	3	310	336	1,246	22
Common raven	100,792	100,578	174,225	39,863	125,464	34,836	50,131	81,905	7,602	85,158	76,661	252,212	47,211
Steller's jay	264,624	46,099	507,164	306,066	784,118	54,598	327,325	191,919	20,945	160,033	553,014	989,382	169,029
Clark's nutcracker	1,897	1,407	6	9	19	2	3	10	149	0	2,990	5,915	4,668
Canada jay	10,186	7,988	25,300	10,092	5,605	41	433	36,395	14,233	8,602	1,942	29,679	22,741
Bullfrog	151	0	2,883	1	527	0	3	0	0	134	2,333	12,018	113
Chicken	130	122	1,729	7	18,107	168	106	716	12	601	959	10,133	28
Cow	3	0	12	0	15	7	0	0	0	28	6	25	1

Sound	CAS	CLE	COA	HJA	KLA	MAR	NWC	OLY	RAI	TYE	CA 2%	OR 2%	WA 2%
Stream noise	730	3,498	20,054	13	817	1,045	19	0	1	895	267	1,062	21
Cricket	57,919	21,163	150,929	158,204	380,592	1,206	327,519	8,091	1,123	194,101	1E+06	2E+06	94,755
Dog	1,174	10,687	3574	103	48,778	3,615	9,801	1,215	6	6,319	12,603	31,451	9,284
Buzzing insect	724,439	227,576	349,242	251,932	300,694	4,519	190,313	502,561	114,592	93,967	622,471	1E+06	364,301
Frog chorus	669,500	449,471	140,399	150,738	618,074	46,967	91,413	243,381	47,708	248,614	290,128	545,478	88,283
Rain	159	856	4,344	1,237	259	3	9	4,315	758	1,119	93	1,480	752
Thunder	1	1	0	0	2	0	0	5	0	0	0	4	0
Tree creaking	9,398	39,486	5,733	1,373	7,682	142	1,471	5,214	3,927	4,104	2,562	17,498	11,482
Coyote	0	1	0	0	0	0	0	0	1	0	1	6	0
American pika	5,238	8,382	9	7,520	39	1	60	30	1,205	2	383	1,258	15,250
Deer snort	57	2	15	19	52	0	20	8	0	16	32	85	34
Douglas squirrel rattle	225,632	292,772	75,383	71,808	22,499	293	33,488	327,846	75,893	30,259	85,120	187,072	276,913
Douglas squirrel chirp	156,040	133,287	29,299	44,349	24,109	62	25,867	185,806	30,117	30,834	73,989	134,092	74,262
Chipmunk spp. chirp	152,033	154,166	117,205	102,107	100,434	1,063	30,572	84,944	68,801	51,012	122,650	339,652	114,107
Black bear juvenile	2	2	3	0	3	0	4	2	1	0	3	9	2
Sandhill crane	68	0	1	0	0	0	0	0	0	0	0	12	0
Canada goose	33,312	2,139	6,321	1,608	14,588	348	144	916	66	3,892	3,270	15,595	99

Sound	CAS	CLE	COA	HJA	KLA	MAR	NWC	OLY	RAI	TYE	CA 2%	OR 2%	WA 2%
California quail	0	0	0	0	12	1,427	0	0	0	7	60	21	0
Common nighthawk "peent"	527,035	51,237	48,074	91,064	54,277	50	12,550	159,492	8,264	34,998	127,520	638,181	190,729
Common nighthawk "boom"	357,166	15,480	38,243	50,528	36,663	24	7,893	43,667	278	26,113	71,880	39,9741	90,866
Sooty grouse	76,763	218,059	29,526	280,894	381,178	2	3,386	1E+06	13,167	589,598	10,614	305,387	130,794
Sooty grouse	10	3	9	8	9	0	3	38	2	2	3	31	27
Wilson's snipe	21	0	0	0	0	0	0	0	0	0	0	0	0
Wild turkey	212	34	112	3	1,818	287	1	3	1	129	533	489	18
Mountain quail	32,903	8	15,318	9,763	376,322	1	72,233	58	4	35,731	246,101	123,703	14,490
Mountain quail	117	19	22	119	520	1	209	5	1	165	2,323	1,048	67
Band-tailed pigeon	11,590	1,263	426,194	23,222	48,286	41,697	8,899	97,384	1,972	25,394	44,874	157,126	16,073
Band-tailed pigeon	16	2	37	15	26	4	9	168	3	8	45	78	17
Common poorwill	101,563	305,622	430	139	37,157	17	9,348	134	7	94	110,518	217,634	54,250
Eurasian collared dove	0	0	3	0	4	0	1	0	0	0	1	37	0
Mourning dove	853	684	1,925	222	21,804	21,299	9,392	190	0	826	81,692	74,790	387
Northern saw-whet owl	154,860	86,123	564,243	26,217	227,644	89,985	40,136	223,311	4,619	176,384	26,880	206,395	54,582

Sound	CAS	CLE	COA	HJA	KLA	MAR	NWC	OLY	RAI	TYE	CA 2%	OR 2%	WA 2%
Long-eared owl	2	2	0	0	0	0	0	0	0	1	1	0	0
Great horned owl song	36,211	87,970	5,674	3,470	22,041	13,782	6,717	12,161	310	10,583	30,581	57,695	26,957
Great horned owl calls	540	1,890	345	223	5,267	140	224	165	17	1,089	1,823	980	369
Northern pygmy-owl	49,845	34,155	670,763	88,882	179,016	703	21,568	75,124	6,069	226237	55,009	285,175	52,394
Western screech-owl trill	7,076	659	48,974	7,874	212,889	93	26,939	4,480	25	41,115	55,249	111,989	6,549
Western screech-owl bark	0	2	4	2	9	0	1	3	0	6	17	16	0
Western screech-owl juvenile	142	9,827	3,154	7,187	190	64	142	400	5	521	9,606	4,016	2,773
Flammulated owl	3,792	285,408	236	41	1,968	68	26,559	48	0	76	38,840	66,583	15,305
Great grey owl	2,459	56	46	284	141	4	52	20	5	14	32	1,200	106
Cooper's hawk series call	19	2	2	1	6	0	2	0	0	0	10	41	9
Northern goshawk series	1,786	1,053	186	844	1,285	51	1,630	881	452	347	1,119	3,525	686
Northern goshawk scream	8,656	2,170	292	1,722	3,531	430	1,858	5,000	1,250	221	20,492	19,468	4,689
Sharp-shinned hawk series call	0	2	9	1	0	0	0	1	0	0	0	2	0
Merlin	7	6	25	16	1	2	28	855	1	4	2	21	6

Sound	CAS	CLE	COA	HJA	KLA	MAR	NWC	OLY	RAI	TYE	CA 2%	OR 2%	WA 2%
American kestrel	168	214	69	30	73	0	13	530	16	37	62	587	404
Raptor scream call	0	2	38	4	14	0	0	35	5	45	5	34	5
Hermit thrush	3E+06	2E+06	115828	1E+06	2E+06	16,810	250,942	185,665	575,849	309,316	571,755	2E+06	1E+06
Hermit thrush	0	2	0	0	2	0	0	0	1	0	0	4	3
Hermit thrush	41,399	15,094	2,182	14,253	20,347	1,128	1,585	2,160	4,833	7,424	4,787	21,851	9,423
Swainson's thrush	109,299	142,869	6E+06	1E+06	69,461	119,009	2,617	340,514	66,385	259,358	11,671	2E+06	481,207
Swainson's thrush	681	319	102,251	5,274	598	2,945	8	4,496	320	3,987	70	31,779	1,803
Olive-sided flycatcher	239,006	151,341	56,398	133,639	95,830	18,762	63,572	135,271	18,785	11,343	172,466	415,650	242,942
Olive-sided flycatcher	50,763	29,953	6,917	13,129	11,839	502	11,584	61,003	7,178	2,892	41,168	73,343	55,951
Wrentit	1,950	27	144,851	31	124,036	40,557	4,805	78	5	25,072	40,955	73,326	1,618
Western wood-pewee	3,707	22,795	4,684	1,261	2,076	71	5,557	2,982	383	1,278	11,859	17,699	10,422
Dusky flycatcher	14,045	13,469	111	217	699	1	2,207	175	37	38	9,052	14,549	1,587
Purple finch	228	1,047	163	21	177	141	79	17	2	24	50	210	40
Varied thrush	8,465	396,916	1E+06	304,711	11,167	75	137	2E+06	485,158	94,448	4,381	492,937	440,403
Varied thrush	1,254	890	1,868	1,422	1,843	473	2,050	3,489	1,603	520	3,513	4,504	2,625
Dark-eyed junco	8,417	13,171	456	4,240	3,685	101	2,059	17,100	4,883	1,187	3,995	15,087	5,625

Sound	CAS	CLE	COA	HJA	KLA	MAR	NWC	OLY	RAI	TYE	CA 2%	OR 2%	WA 2%
Red crossbill	0	0	695	0	1	0	0	551	1	0	0	4,493	11
Townsend's solitaire	80,682	47,426	1,124	39,477	38,514	39	19,817	12,057	1,184	4,268	46,642	106,424	43,809
Western tanager call	0	0	10	3	4	0	10	2	0	0	2	5	1
Spotted towhee call	5,100	119	7,675	1,430	11,903	10,871	18,048	51	11	4,711	23,018	20,979	1,975
Chickadee song	111,686	12,997	30	88	200	6	1,739	75	719	24	25,932	104,349	1,222
Chickadee call	1,712	1,041	0	4	0	0	65	0	35	0	858	1,691	291
Mountain bluebird	66	314	0	0	0	0	1	1	0	1	0	17	31
Nuthatch spp	3E+06	2E+06	780,477	1E+06	2E+06	24,374	569,048	1E+06	608,117	837,061	1E+06	3E+06	1E+06
Nuthatch spp	734	868	115	247	104	0	48	152	6	40	145	719	83
American robin whinny	10,678	7,876	19,124	9,540	11,848	1,144	3,048	33,165	944	9,969	4,409	22,841	5,213
American robin other calls	2,618	1,142	5,554	2,831	3,103	95	2,483	6,520	172	2,739	2,902	7,220	2,374
Hutton's vireo	0	0	34	1	41	0	14	12	0	12	3	20	1
Northern flicker series call	64,545	28,576	26,648	25,809	153,832	3,741	27,231	11,072	1,569	53,527	28,376	91,929	14,212
Northern flicker "skew"	8,246	3,905	2,858	2,535	13,858	239	3,229	7,388	826	6,577	11,622	19,933	6,365
Downy woodpecker	144	6	1	3	22	1	9	16	3	5	159	466	5
Woodpecker (non-	22,725	17,752	12,965	6,098	20,203	1,696	4,312	13,345	902	6,696	10,701	32,129	6,350

Sound	CAS	CLE	COA	HJA	KLA	MAR	NWC	OLY	RAI	TYE	CA 2%	OR 2%	WA 2%
sapsucker)													
Pileated woodpecker	36,897	10,568	51,778	16,087	50,028	3,931	9,892	23,356	1,239	27,736	29,588	73,342	10,592
White-headed woodpecker	10	13	5	0	0	0	140	0	0	0	1131	63	11
Hairy woodpecker	386	188	340	225	255	15	147	311	43	78	433	546	261
Acorn woodpecker	2	1	0	1	587	47	1,402	0	0	0	1,626	1,535	5
Sapsucker spp drum	3,508	2,243	6,227	1,761	2,424	1	650	3,476	210	3,623	1,059	6,278	1,437

[a] Validated counts from full review at the 0.5 threshold.

Table 6. Proportion of monitored hexagons with validated detections of northern spotted owl for years that surveys were conducted (2018–2023) within the Northwest Forest Plan Area.

Area	2018	2019	2020	2021	2022	2023
COA	0.16	0.13	0.09	0.15	0.09	0.11
OLY	0.16	0.17	0.24	0.19	0.27	0.25
KLA		0.43	0.53	0.49	0.51	0.37
CLE			0.19	0.19	0.11	0.20
CAS				0.35	0.31	0.23
HJA				0.39	0.39	0.43
MAR				1.00	1.00	1.00
NWC				0.77	0.73	0.80
RAI				0.09	0.04	0.06
TYE				0.38	0.28	0.15
WA 2%					0.00[a]	0.09
OR 2%					0.54[a]	0.24
CA 2%						0.37

[a] In 2022, Gifford Pinchot National Forest in Washington and Umpqua National Forest in Oregon were sampled at 2%.

Table 7. Proportion of monitoring hexagons with validated detections of marbled murrelet for years that surveys were conducted (2018–2023) within the Northwest Forest Plan Area.

Area	2018	2019	2020	2021	2022	2023
COA	0.83	0.75	0.79	0.82	0.86	0.91
OLY	0.78	0.85	0.84	0.87	0.85	0.92
KLA		0.00	0.00	0.01	0.00	0.01
CLE			0.00	0.00	0.00	0.00
CAS				0.00	0.00	0.00
HJA				0.00	0.00	0.00
MAR				0.00	0.00	0.00
NWC				0.00	0.00	0.00
RAI				0.09	0.13	0.13
TYE				0.15	0.10	0.05
WA 2%					0.00[a]	0.13
OR 2%					0.08[a]	0.20
CA 2%						0.01

[a] In 2022, only Gifford Pinchot National Forest in Washington and Umpqua National Forest in Oregon were sampled at 2%.

Table 8. Proportion of monitoring hexagons with validated detections of barred owls for years that surveys were conducted (2018–2023) within the Northwest Forest Plan Area.

Area	2018	2019	2020	2021	2022[a]	2023
COA	0.99	0.99	1.00	0.99	1.00	0.99
OLY	0.92	0.93	0.93	0.90	0.94	0.93
KLA		0.86	0.95	0.95	1.00	0.97
CLE			0.77	0.65	0.79	0.80
CAS				0.95	0.96	0.94
HJA				0.99	0.99	0.97
MAR				0.29	0.86	0.14
NWC				0.73	0.73	0.67
RAI				0.82	0.88	0.94
TYE				1.00	1.00	1.00
WA 2%					0.65[b]	0.93
OR 2%					0.46[b]	0.84
CA 2%						0.37

[a] In 2022, we didn't extensively validate barred owl classes, thus adjusted PNW-Cnet model predicted proportions are reported.

[b] In 2022, only Gifford Pinchot National Forest in Washington and Umpqua National Forest in Oregon were sampled at 2%.

11. Figures

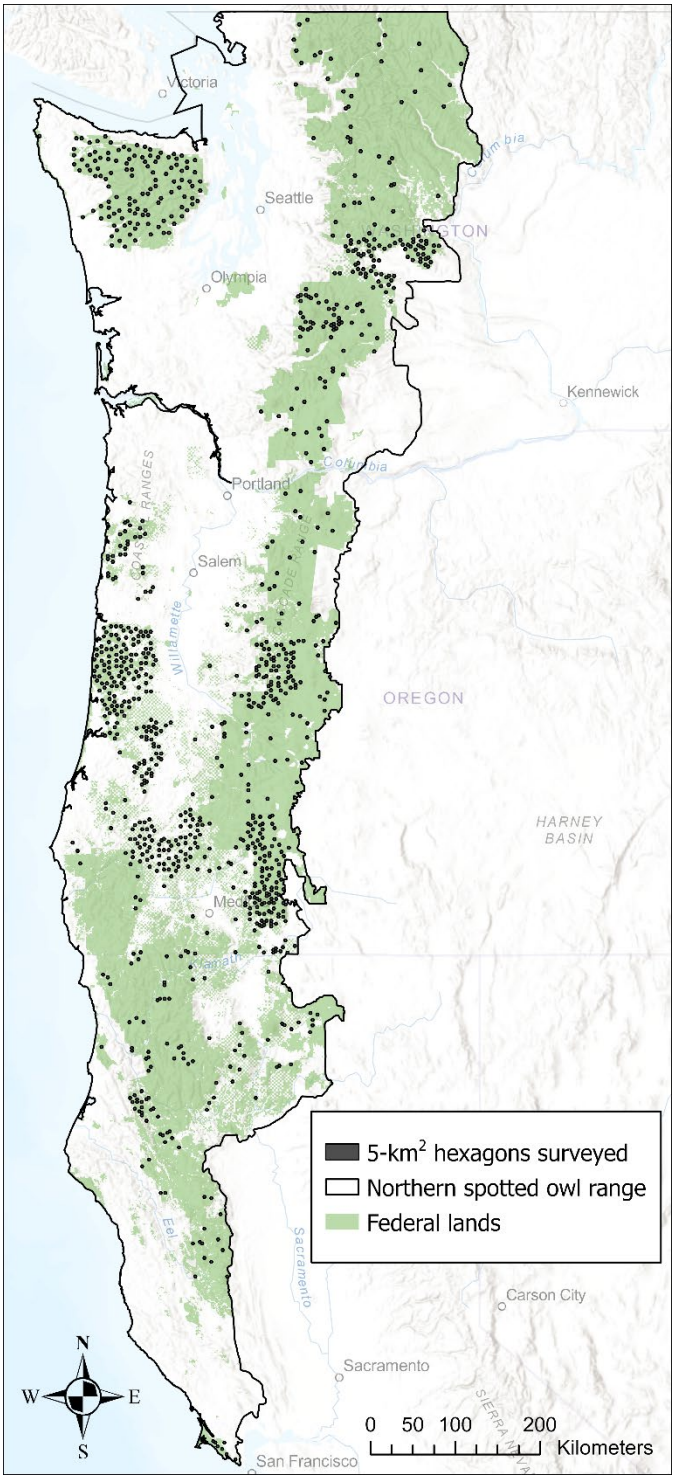

Figure 1. Locations of 5-km^2 hexagons (n =1,009) surveyed on federal lands using passive acoustic monitoring in 2023.

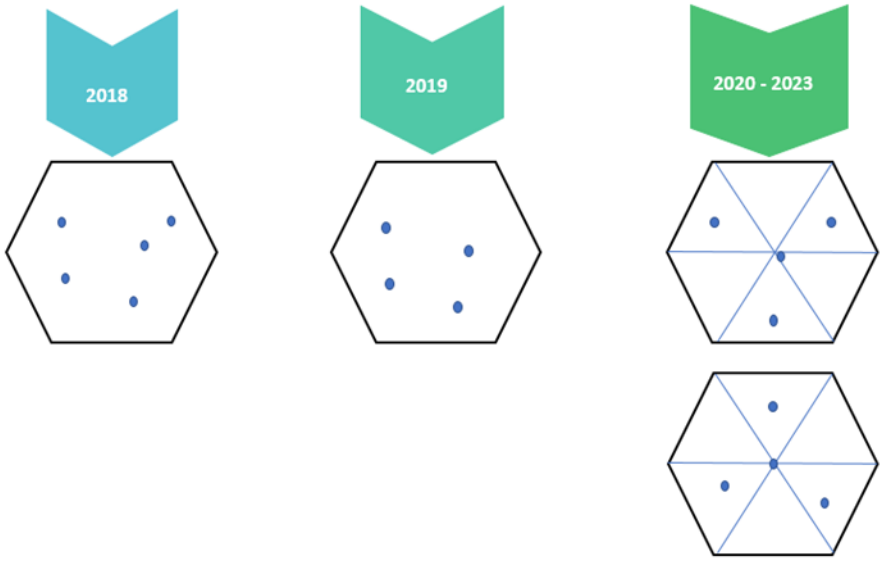

Figure 2. Example sampling station layouts by year. In 2018, five sampling stations were randomly placed within hexagons (no further than 1.5 km from a road or trail) following this rule set: on federal land; mid-to-upper slope positions; ≥ 50 m from roads, trails, and streams; spaced ≥ 500 m apart; and located ≥ 200 m from edge of hexagon. Starting in 2019, established hexagons on COA and OLY had one sampling station randomly removed based on sampling design change, leaving four sampling stations. Newly established hexagons in KLA during 2019 had four random sampling stations selected following within-hexagon placement rule set established in 2018. Newly established hexagons in 2020 - 2023 followed a more standard sampling station layout with one station centrally located and three stations in non-adjacent triangles within the hexagons. Other within-hexagon placement rules established in 2018 was also applied, thus some stations needed to be adjusted to meet rule set requirements.

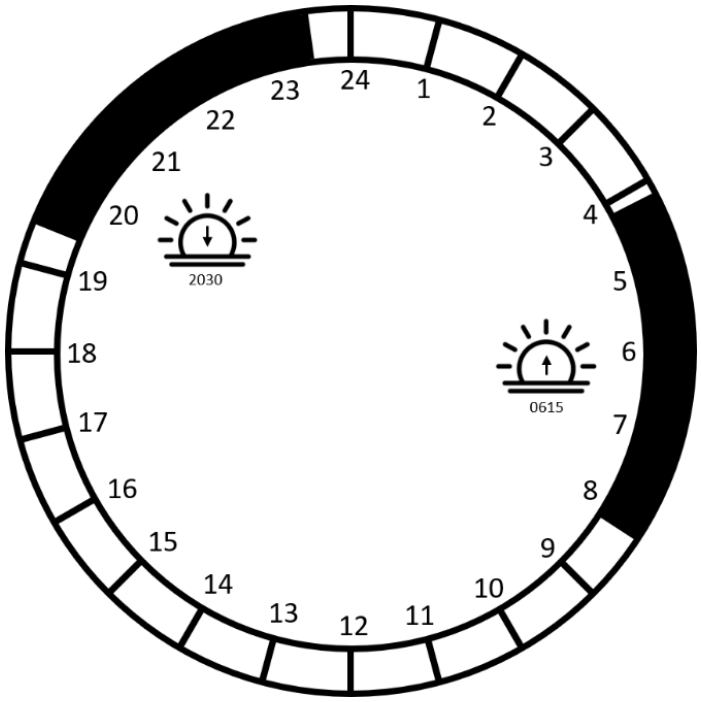

Figure 3. Example 24 h diel cycle (sunrise at 0615, sunset at 2030) recording schedule used on autonomous recording units to conduct passive acoustic monitoring within the Northwest Forest Plan area. Recording times shown with black bars occurring during 4 h blocks during crepuscular period and 10 minutes each hour. The first daily crepuscular block recording starts 2 h before (0415) and ends 2 h after (0815) sunrise, and the second block recording starts 1 h before (1930) and ends 3 h after (2330) sunset.

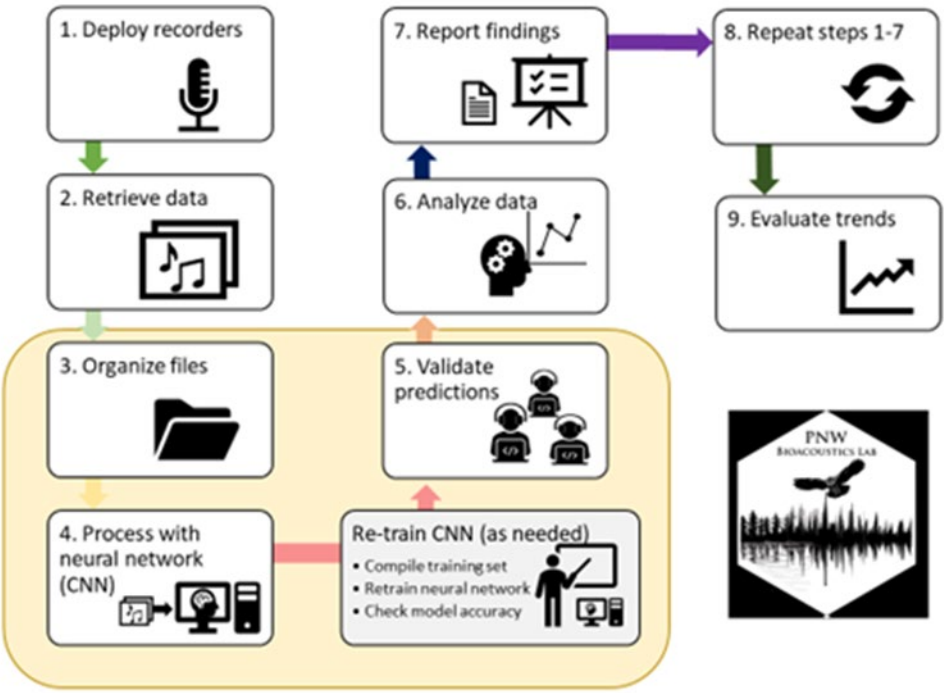

Figure 4. Workflow for the passive acoustic monitoring program within the Northwest Forest Plan area. The process includes data collection, training the convolutional neural network (PNW-Cnet) for automated species identification, processing data, analyzing data, and reporting findings. Highlighted are steps 3–5 which are steps focused primarily on data processing.

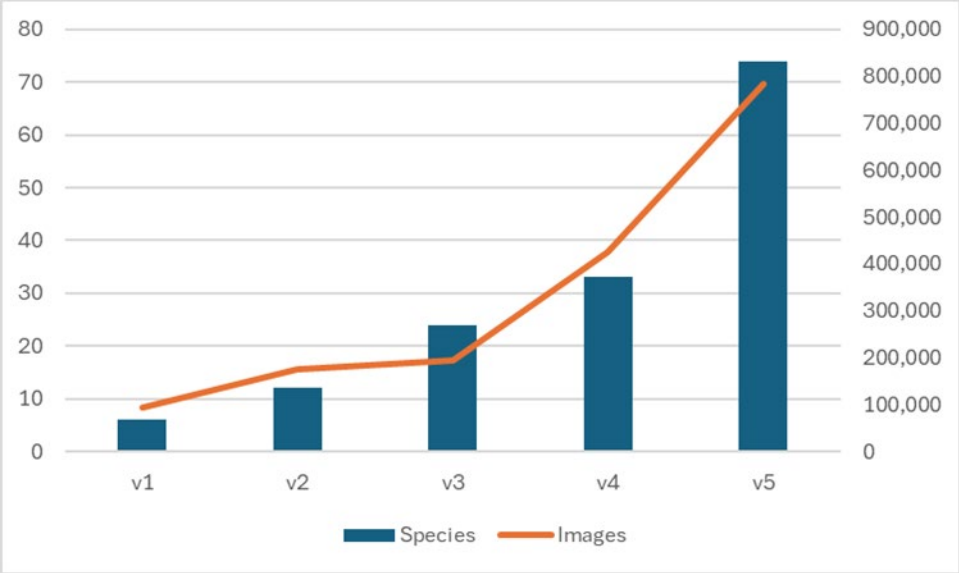

Figure 5. PNW-Cnet version with number of wild species identified to species level (primary y-axis) and sample size of images used in model training set (secondary y-axis) (Ruff et al. 2020, Ruff et al. 2021, Ruff et al. 2023).

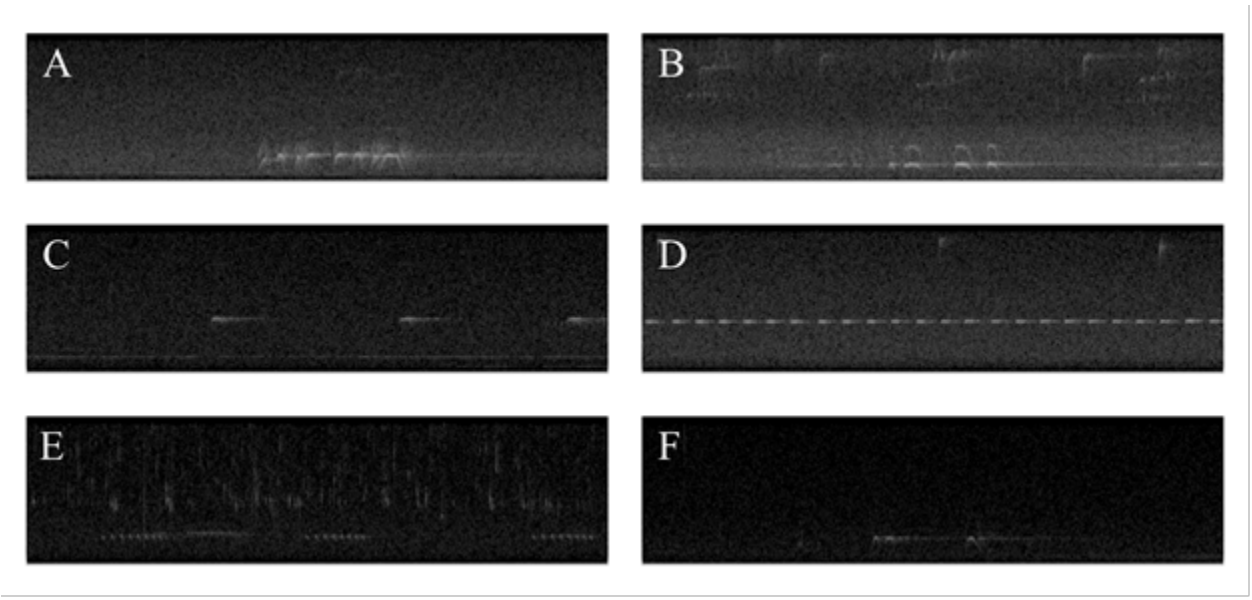

Figure 6. Example spectrogram images of target species calls used by Ruff et al. (2020) to train PNW-Cnet to detect owl calls in field recordings. A = barred owl, B = great horned owl, C = northern pygmy owl, D = northern saw-whet owl, E = western screech owl, F = northern spotted owl. Each spectrogram is 500 x 129 resolution and represents 12 s of audio in the frequency range 0-3000 Hz. Spectrograms like those shown were used in PNW-Cnet v1 and v2. From PNW-Cnet v3 and v4, spectrograms were 1000 x 257 resolution and included the frequency range 0-4000 Hz. Lighter areas represent greater sound intensity.