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1. Title

Passive Acoustic Monitoring within the Northwest Forest Plan Area: 2022 Annual Report

2. Research Team

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3. Introduction

Northern spotted owl (*Strix occidentalis caurina*; hereafter NSO) populations have been monitored since the 1990's as part of the Northwest Forest Plan 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 NSO geographic range, as well as identifying barred owls (*S. varia*) and available habitat as important factors associated with those trends (Lesmeister et al. 2018, Yackulic et al. 2019, Franklin et al. 2021).

Two phases were envisioned in the establishment of the NSO population monitoring program (Lint et al. 1999). Phase I 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 eight 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). Phase II requires, in addition to habitat monitoring, an analytical framework coupled with species survey data to assess trends in the populations (Lesmeister et al. 2021).

Passive acoustic monitoring using autonomous recording units (ARUs) has been demonstrated to be effective for conducting surveys for NSO and barred owls (Duchac et al. 2020), distinguishing NSO sex (Dale et al. 2022), establishing pair status (Appel et al. 2023), integrating with traditional territory survey data (Weldy et al. 2023), and detecting trends in NSO populations (Lesmeister et al. 2021). Further, ARUs allow for extended-duration sessions, which greatly decreases field technician effort 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 NSO and a wide range of other vocal wildlife species (Ruff et al. 2020, Ruff et al. 2021, Ruff et al. 2023). In 2020, the Northwest Forest Plan Regional Interagency Executive Committee decided to discontinue Phase I and transition to Phase II over a two-year period. Phase II includes habitat monitoring coupled with a passive acoustic monitoring survey network (Lesmeister and Jenkins 2022).

Here we provide a progress report on passive acoustic monitoring conducted during 2022—the second year of the transition in methods for the NSO monitoring program—within the Northwest Forest Plan area. We report on survey effort using ARUs in 5 km^2 hexagons and survey results for NSO and 35 other species. Marbled murrelet (*Brachyramphus marmorantus*; hereafter MAMU) populations are also monitored under Northwest Forest Plan effectiveness monitoring and are included in our automated species detection model; therefore, for NSO and MAMU, we also report the proportion of hexagons and ARU stations with validated detections for years 2018–2022.

4. Study Area

We collected data within 10 historical NSO demographic study areas and two national forests with lands that were primarily under federal ownership and administered by US Forest Service, US Bureau of Land Management, or National Park Service (Fig. 1). We surveyed approximately 20% of available hexagons on the 10 study areas. Nine of the study areas (OLY = Olympic Peninsula, CLE = Cle Elum, RAI = Mt. Rainer National Park, COA = Oregon Coast Range, HJA = HJ Andrews Experimental Forest, TYE = Tyee, KLA = Klamath, CAS = South Cascades, NWC = Northwest California) were long-term demographic study areas for NSO monitoring under the Northwest Forest Plan (Franklin et al. 2021), one study area (MAR = Marin County) was included due to long-term and ongoing NSO demographic monitoring (Fig. 1). We surveyed approximately 2% of available hexagons on two national forests (UMP = Umpqua National Forest, GIP = Gifford Pinchot National Forest).

5. Methods

Sampling design

We created a uniform layer of 5 km^2 hexagons that covered the entire range of the NSO (Lesmeister et al. 2021) which is now publicly available for download (USFWS 2021). This hexagon size is approximately the size of a NSO 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 10 historical NSO study areas we randomly selected approximately 20% of hexagons that contained ≥50% forest capable lands and ≥25% federal ownership. We randomly sampled approximately 2% of the available hexagons on the two national forest areas. 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 provide a buffer between territories and reduce the probability of detecting the same individual in multiple hexagons.

Following the first step in our monitoring program workflow (Appendix A), we established four sampling stations within in each hexagon (Appendix B) during the survey season, March-August 2022. At each sampling point we mounted an ARU to a small diameter tree (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 hexagon. We retrieved ARUs and acoustic data after 6 weeks of survey.

We collected acoustic data using Song Meter SM4 (Wildlife Acoustics, Maynard, MA) ARUs, which were portable, weatherproof, and easily programmable. The SM4s had two built-in omni-directional microphones with signal-to-noise ratio of 80 dB typical at 1 kHz, two SDHC/SDXC flash card slots, 350–400 h battery life, and a recording bandwidth of 20 Hz to 48 kHz at decibel levels of -33.5 dB to 122 dB. SM4s 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. We programmed ARUs to record for two four-hour blocks during crepuscular periods and 10 minutes each hour of the diel cycle (Fig. 2).

Data processing

We have developed four versions of a convolutional neural network model (PNW-Cnet) to automate detections of vocal wildlife species, with each version attaining improved performance and greater number of species identified compared to each preceding version (Appendix C, D). Details on development of previous versions of PNW-Cnet can be found in Ruff et al. (2020), Ruff et al. (2021), and in the 2021 annual report (Lesmeister et al. 2022). We processed data reported here with PNW-Cnet v4 (Ruff et al. 2023) that included 45 sound classes for 36 individual species (Table 1) and was trained on 426,605 training images. To determine the performance of PNW-Cnet v4 to correctly classify each sound class, we calculated precision and recall, generated from a test set of clips that were fully reviewed by human technicians (Table 1). 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.

We used a multi-step workflow (Appendix A) that integrated PNW-Cnet v4 to efficiently process large volumes of audio data, combining automated identification and human validation (Ruff et al. 2021, Ruff et al. 2023). 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. PNW-Cnet v4 generated predictions (interpretable as probabilities between 0–1) for each sound class for each 12 s clip of sound. We used a prediction threshold of ≥ 0.95 for most sound classes to determine the predicted number of detections of each sound class for each study area. To ensure we identified as many NSO calls as possible, we also selected a prediction threshold of 0.25 for NSO call classes, which resulted in lower precision but higher recall than the 0.95 threshold (Table 1; Ruff et al. 2021). This resulted in the need to manually review a greater number of sound clips during validation but increased the overall number of NSO detections.

Data validation

Output from PNW-Cnet v4 for NSO and MAMU detections were further validated through a process of review by trained human technicians. The validation process consisted of reviewing 12 s clips that met our model prediction threshold (> 0.25 for NSO location call, > 0.95 for MAMU keer call). We validated all NSO calls that met the threshold and a subset of all MAMU keer calls to confirm weekly presence at the sampling station. We used the program Kaleidoscope Pro (Wildlife Acoustics) for validating PNW-Cnet v4 output by examining the audio and spectrogram to confirm a correct prediction or apply corrected sound class tags (Fig. 3). After identifying validated NSO calls, we further classified high quality NSO four-note location calls as female, male, or unknown sex based on frequency and call length measurements using a logistic regression model developed by Dale et al. (2022). We report the proportion of surveyed ARU stations and hexagons with validated detections for NSO and MAMU. For all other sound classes we report the estimated number of detections for each class, which was PNW-Cnet v4 model output corrected by the model precision (Table 1) for each class.

Removal of data affected by call-back surveys

Call-back surveys for NSO 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 management operation clearance. These surveys broadcast recorded calls of NSO, 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 NSO 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 removed any validated detections 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.

6. Results

This was the first year of sampling for the 2% areas, UMP and GIP (Fig. 1). In 2022, 526 of our sampling stations were in designated Wilderness Areas administered by US National Park Service (*n* = 388) or US Forest Service (*n* = 188; Table 2). We surveyed 2,748 sampling stations in 690 hexagons with nearly 1.5 million hours of recordings (Table 3; Table 4). The amount of data collected, and area surveyed has increased each year over the five years of passive acoustic monitoring (Table 3; Table 4; Appendix D). Spotted owl call-back surveys were reported on all study areas.

PNW-Cnet v4 generated predicted detections for all target species (Table 5). We documented 27,813 NSO detections (6,497 series and 21,316 location calls). Of the location calls, 6,735 were of high enough quality for sex prediction and 5,454 were categorized as male or female after survey nights were removed. NSO males were much more commonly detected than females (Table 5). The highest NSO call counts were found in CAS, KLA and MAR, followed by HJA, NWC, and OLY, then COA, CLE, TYE, and UMP (Table 5). The California study areas had the highest proportion of occupied hexagons and stations in both 2021 and 2022 (Table 6). Areas in the Washington Cascade Range (CLE, RAI, GIP) had the lowest proportions of NSO occupancy (Table 6). We documented only two NSO detections on RAI and no detections on GIP, which are adjacent lands in the Washington Cascades (Table 5). We detected over 3,900 MAMU keer calls on COA and OLY, and a small number of detections on RAI, TYE and UMP (Table 5), which were also reflected in the proportion of hexagons and stations used in each study area (Table 7).

7. Discussion

In 2020, the Northwest Forest Plan Regional Interagency Executive Committee decided to transition to Phase II, consisting of habitat monitoring coupled with passive acoustic monitoring on 20% of hexagons in former demographic study areas and 2% of all other hexagons in federal forests within the range of the NSO. In 2021 we expanded passive acoustic monitoring to all former NSO demography sites at approximately 20% sampling density with an overlap of demography and bioacoustics of at least one year on most study areas (Lesmeister et al. 2021). In 2022, we piloted two additional 2% areas of matrix between study areas, UMP and GIP, with the goal of sampling the full 2% range-wide federal forest sample in 2023.

We designed range-wide templates for our hexagon sampling design that can be expanded and used for sampling design anywhere within the range of NSOs (USFWS 2021). Additionally, our flexible ARU placement design, with four ARUs per hexagon placed either randomly or in a stratified design (Appendix B) on forested land (following the rule set for available areas within a hexagon) could easily be adapted to accomplish surveys with diverse objectives while enabling collaborators to potentially contribute to the larger monitoring network.

Over the last four years, we have improved our ability to efficiently process and validate increasingly large volumes of acoustic data. This is due to a range of improvements in data processing workflows, PNW-Cnet performance, recent increases in field and validation staff stability, and protocols that have shifted from a testing to implementation phase. Clearing bioacoustics data of NSO call-back surveys is a primary factor constraining workflow speed in producing final datasets for NSO analyses, but surveyors are increasingly aware of the passive acoustic monitoring program and processes are in place to expedite call-back survey information sharing. We expect continued improvement in the speed at which we provide final hexagon and station naïve occupancy results for all species included in our automated identification list.

We now have enough years of data to begin to evaluate trends in NSO populations and our naïve occupancy estimates align well with occupancy estimates from other studies (Dugger et al. 2016, Yackulic et al. 2019, Franklin et al. 2021, Wiens et al. 2021, Appel et al. 2023, Weldy et al. 2023). We also found that barred owls are nearly ubiquitous throughout all study areas, so few locations remain for NSO to establish territories without harassment by barred owls. By using a low automated detection score threshold combined with full manual review of all potential detections for NSO classes, we are confident we maximized detections of NSO. Although the low score threshold entails lower precision and hence yields a greater number of false positives, reviewing these potential detections is still a reasonable investment of effort for this ESA-listed species. While the NSO location call can be classified as male or female, most recordings do not meet sound quality necessary for high precision model classification. And of those that can be classified, the majority are classified as male or unknown. This is likely due to differences in vocal behavior and space use between the sexes during the breeding season. Females are less likely to move away from the territory core, and less frequently engage in territorial calling bouts (D. Lesmeister, unpublished data). (Reid et al. 1999). Additionally, since we are using a random hexagon placement, which will enable extrapolation of habitat use rangewide, many surveys do not occur within a territory core or nest site, reducing the likelihood of female detection.

The biggest challenge to producing occupancy estimates for NSO has been identifying calls originating from human surveyors using broadcast play-back surveys. Broadcast surveys have been the primary method of determining NSO 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 NSO call-back surveyors in Oregon and Washington (e.g., Bureau of Land Management, Forest Service, state agencies) has greatly enhanced our ability to screen out and identify call-back surveys during human review and should expedite occupancy estimates for those overlapping survey areas.

Marbled murrelets were the only other species in addition to NSO for which we performed full human validation of weekly detections in 2022. We detected murrelets in highest quantity and coverage in study areas within the core of their breeding range (COA, OLY). However, we were also able to detect murrelets on the edge of their known range, where any detections are rare or notable (TYE, UMP, RAI). This highlights the utility of broadscale random sampling coupled with efficient data processing for elusive species monitoring. Further, the extraction of non-NSO target class detections has demonstrated the robustness of passive acoustic monitoring for multi-species monitoring and community-level analyses and has helped to improve model predictions for NSO (Ruff et al. 2021). The number of species and sound classes has increased from 17 sound classes in 2018 to 51 sound classes in 2022 (Ruff et al. 2023). Although some of the additional sound classes have not been of immediate interest (e.g., dog barking and chickadee calls), the inclusion of these classes improves the PNW-Cnet performance for other sound classes and provides opportunities for wildlife community-level analysis or other collaborative projects (Lesmeister and Jenkins 2022). We have also incorporated sound classes for species of interest to collaborators and other population monitoring teams, including the marbled murrelet, gray wolf (*Canis lupus*), and sooty grouse.

As the geographical scope of sampling increases, PNW-Cnet sound class predictive performance is expected to initially be lower in new regions. This is due to variation in background noise and vocal community composition at new sites that are not yet encompassed by model training sets. With expansion to new locations, we may encounter species not yet incorporated as a PNW-Cnet class and have vocalizations with spectrograms that resemble other target classes. For example, PNW-Cnet v3 predicted >2,500 clips as containing possible marbled murrelet flight calls in CLE and KLA study areas, which are largely outside of the range of the species. PNW-Cnet v4 predicted <500 clips in those same areas for marbled murrelet, indicating improved model performance and discrimination from other sounds. We also have PNW-Cnet v4 predicted flammulated owl detections outside the geographic range that will be cleared through validation, and we expect fewer of these "false positives" with further trainings of the model. Beyond these examples, we will continue to expand and improve our training sets and performance of future PNW-Cnet versions. Manual review and confirmation of sound class presence will continue to be important as new sites and sound classes are added to the monitoring program. Manual review of apparent detections by humans ensures that our hexagon occupancy status for each target class is accurate and has the secondary benefit of producing additional training data which can be added to future versions of PNW-Cnet.

One of our goals has been to increase benefits of passive acoustic monitoring by making the methods more accessible to landowners, wildlife biologists and others interested in monitoring wildlife activity. Therefore, we developed and published a desktop application which performs the same audio processing and PNW-Cnet classification following our protocols (Ruff et al. 2021, Ruff et al. 2023). This application is freely available and can be run using only open-source software including RStudio, Keras / TensorFlow, and SoX. Users can process large volumes of audio data at a reasonable speed on consumer-grade personal computers and review and extract apparent detections. Results will be directly comparable to those obtained through the monitoring program; to the extent that the sampling regime is similar, and the results are shared publicly, this effectively expands the spatial extent of the monitoring program.

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9. Literature Cited

Appel, C. L., D. B. Lesmeister, A. Duarte, R. J. Davis, M. J. Weldy, and T. Levi. 2023. Using passive acoustic monitoring to estimate northern spotted owl landscape use and pair occupancy. Ecosphere 14:e4421.

Dale, S. S., J. M. A. Jenkins, Z. J. Ruff, L. S. Duchac, C. E. McCafferty, and D. B. Lesmeister.

2022. Distinguishing sex of northern spotted owls with passive acoustic monitoring. Journal of Raptor Research 56:287-299.
Davis, R. J., and J. Lint. 2005. Habitat status and trends. Pages 21-82 *in* J. Lint, editor. Status and Trends of Northern Spotted Owl Populations and Habitat. PNW-GTR-648. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.
Duchac, L. S., D. B. Lesmeister, K. M. Dugger, Z. J. Ruff, and R. J. Davis. 2020. Passive acoustic monitoring effectively detects Northern Spotted Owls and Barred Owls over a range of forest conditions. The Condor 122:1-22.
Dugger, K. M., E. D. Forsman, A. B. Franklin, R. J. Davis, G. C. White, C. J. Schwarz, K. P. Burnham, J. D. Nichols, J. E. Hines, C. B. Yackulic, P. F. Doherty Jr., L. L. Bailey, D. A. Clark, S. H. Ackers, L. S. Andrews, B. Augustine, B. L. Biswell, J. A. Blakesley, P. C. Carlson, M. J. Clement, L. V. Diller, E. M. Glenn, A. Green, S. A. Gremel, D. R. Herter, J. M. Higley, J. Hobson, R. B. Horn, K. P. Huyvaert, C. McCafferty, T. L. McDonald, K. McDonnell, G. S. Olson, J. A. Reid, J. Rockweit, V. Ruiz, J. Saenz, and S. G. Sovern. 2016. The effects of habitat, climate and Barred Owls on the long-term population demographics of Northern Spotted Owls. Condor 118:57-116.
Franklin, A. B., D. R. Anderson, E. D. Forsman, K. P. Burnham, and F. W. Wagner. 1996. Methods for collecting and analyzing demographic data on the Northern Spotted Owl. Studies in Avian Biology 17:12-20.
Franklin, A. B., K. M. Dugger, D. B. Lesmeister, R. J. Davis, J. D. Wiens, G. C. White, J. D. Nichols, J. E. Hines, C. B. Yackulic, C. J. Schwarz, S. H. Ackers, L. S. Andrews, L. L. Bailey, R. Bown, J. Burgher, K. P. Burnham, P. C. Carlson, T. Chestnut, M. M. Conner, K. E. Dilione, E. D. Forsman, E. M. Glenn, S. A. Gremel, K. A. Hamm, D. R. Herter, J. M. Higley, R. B. Horn, J. M. Jenkins, W. L. Kendall, D. W. Lamphear, C. McCafferty, T. L. McDonald, J. A. Reid, J. T. Rockweit, D. C. Simon, S. G. Sovern, J. K. Swingle, and H. Wise. 2021. Range-wide declines of northern spotted owl populations in the Pacific Northwest: A meta-analysis. Biological Conservation 259:109168.
Glenn, E. M., M. C. Hansen, and R. G. Anthony. 2004. Spotted owl home-range and habitat use in young forests of western Oregon. Journal of Wildlife Management 68:33-50.
Hamer, T. E., E. D. Forsman, and E. M. Glenn. 2007. Home range attributes and habitat selection of Barred Owls and Spotted Owls in an area of sympatry. Condor 109:750-768.
Lesmeister, D. B., C. L. Appel, R. J. Davis, C. B. Yackulic, and Z. J. Ruff. 2021. Simulating the effort necessary to detect changes in northern spotted owl (Strix occidentalis caurina) populations using passive acoustic monitoring. Res. Pap. PNW-RP-618. Volume PNW-RP-618.USDA Forest Service, Pacific Northwest Research Station, Portland, OR.
Lesmeister, D. B., R. J. Davis, P. H. Singleton, and J. D. Wiens. 2018. Northern spotted owl habitat and populations: status and threats. Pages 245-298 *in* T. A. Spies, P. A. Stine, R. Gravenmier, J. W. Long, andM. J. Reilly, editors. Synthesis of Science to Inform Land Management within the Northwest Forest Plan Area. PNW-GTR-966. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.
Lesmeister, D. B., and J. M. A. Jenkins. 2022. Integrating new technologies to broaden the scope of northern spotted owl monitoring and linkage with USDA forest inventory data. Frontiers in Forests and Global Change 5:966978.
Lesmeister, D. B., J. M. A. Jenkins, Z. J. Ruff, R. J. Davis, C. L. Appel, A. D. Thomas, S. Gremel, D. Press, T. Chestnut, J. K. Swingle, T. Wilson, D. C. Culp, H. Lambert, C. McCafferty, K. Wert, B. Henson, L. Platt, D. Rhea-Fournier, and S. Mitchell. 2022. Passive Acoustic Monitoring within the Northwest Forest Plan Area: 2021 Annual Report. USDA Forest Service, Pacific Northwest Research Station. https://www.fs.usda.gov/r6/reo/monitoring/downloads/reports/bioacoustics-2021-annual-

report-final.pdf.
Lint, J., B. Noon, R. Anthony, E. Forsman, M. Raphael, M. Collopy, and E. Starkey. 1999. Northern Spotted Owl Effectiveness Monitoring Plan for the Northwest Forest Plan. USDA Forest Service, Pacific Northwest Research Station. Report PNW-GTR-440.
Reid, J. A., R. B. Horn, and E. D. Forsman. 1999. Detection rates of spotted owls based on acoustic-lure and live-lure surveys. Wildlife Society Bulletin 27:986-990.
Ruff, Z. J., D. B. Lesmeister, C. L. Appel, and C. M. Sullivan. 2021. Workflow and convolutional neural network for automated identification of animal sounds. Ecological Indicators 124:107419.
Ruff, Z. J., D. B. Lesmeister, L. S. Duchac, B. K. Padmaraju, and C. M. Sullivan. 2020. Automated identification of avian vocalizations with deep convolutional neural networks. Remote Sensing in Ecology and Conservation 6:79-92.
Ruff, Z. J., D. B. Lesmeister, J. M. A. Jenkins, and C. M. Sullivan. 2023. PNW-Cnet v4: Automated species identification for passive acoustic monitoring. SoftwareX 101473.
Schilling, J. W., K. M. Dugger, and R. G. Anthony. 2013. Survival and home-range size of northern spotted owls in southwestern Oregon. Journal of Raptor Research 47:1-14.
Singleton, P. H., J. F. Lehmkuhl, W. L. Gaines, and S. A. Graham. 2010. Barred owl space use and habitat selection in the eastern Cascades, Washington. Journal of Wildlife Management 74:285-294.
Tegeler, A. K., M. L. Morrison, and J. M. Szewczak. 2012. Using extended-duration audio recordings to survey avian species. Wildlife Society Bulletin 36:21-29.
USFWS. 2021. Northern Spotted Owl Recovery Information Site: Survey Protocol https://www.fws.gov/oregonfwo/Species/Data/NorthernSpottedOwl/SurveyProtocol.asp. *in* US Fish and Wildlife Service, Oregon Fish and Wildlife Office, Pacific Region Ecological Services, Portland, OR.
Weldy, M. J., D. B. Lesmeister, C. B. Yackulic, C. L. Appel, C. McCafferty, and J. D. Wiens. 2023. Long-term monitoring in transition: Resolving spatial mismatch and integrating multistate occupancy data. Ecological Indicators 146:109815.
Wiens, J. D., R. G. Anthony, and E. D. Forsman. 2014. Competitive interactions and resource partitioning between northern spotted owls and barred owls in Western Oregon. Wildlife Monographs 185:1-50.
Wiens, J. D., K. M. Dugger, J. M. Higley, D. B. Lesmeister, A. B. Franklin, K. A. Hamm, G. C. White, K. E. Dilione, D. C. Simon, R. R. Bown, P. C. Carlson, C. B. Yackulic, J. D. Nichols, J. E. Hines, R. J. Davis, D. W. Lamphear, C. McCafferty, T. L. McDonald, and S. G. Sovern. 2021. Invader removal triggers competitive release in a threatened avian predator. Proceedings of the National Academy of Sciences 118:e2102859118.
Yackulic, C. B., L. L. Bailey, K. M. Dugger, R. J. Davis, A. B. Franklin, E. D. Forsman, S. H. Ackers, L. S. Andrews, L. V. Diller, S. A. Gremel, K. A. Hamm, D. R. Herter, M. Higley, R. B. Horn, C. McCafferty, J. A. Reid, J. R. Rockweit, and S. G. Sovern. 2019. The past and future roles of competition and habitat in the rangewide occupancy dynamics of Northern Spotted Owls. Ecological Applications 29:e01861.

10. Tables

Table 1. Precision and recall estimates for each sound class in PNW-Cnet v4, which was used to process bioacoustics data collected during 2022 (Ruff et al. 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 120,269 spectrogram images.

Sound class	Precision	Recall
Northern spotted owl location call (Threshold = 0.95)	0.7642	0.4534
Northern spotted owl location call (Threshold = 0.25)	0.2790	0.9330
Strix owl contact whistle[a]	0.9524	0.4545
Barred owl eight-note	0.9834	0.6085
Barred owl series	0.9921	0.5644
Barred owl inspection	0.9769	0.8025
Great horned owl	0.9930	0.8944
Flammulated owl	0.7792	0.9093
Western screech-owl	0.9945	0.8642
Northern pygmy-owl	0.9865	0.8624
Northern saw-whet owl	0.9789	0.9082
Marbled murrelet	0.9881	0.9323
Common raven	0.9293	0.7745
Steller's jay	0.9648	0.3187
Canada jay	0.9591	0.7629
Sooty grouse	0.9819	0.6066
Pileated woodpecker	0.9229	0.7482
Woodpecker drum	0.6364	0.0074
Northern flicker series	0.9356	0.8896
Sapsucker *spp* drum[b]	0.5000	0.0042
Wrentit	0.9853	0.7819
Common nighthawk call	1.0000	0.1429
Common nighthawk dive	0.8182	0.2647
Hermit thrush	0.9911	0.4483
Swainson's thrush	0.9790	0.6529
Varied thrush	0.9990	0.3013
Mountain quail	0.6273	0.1285
Band-tailed pigeon	0.9895	0.8507
Common poorwill	0.7418	0.7031
Spotted towhee	0.9508	0.5918
Chickadee *spp*[c]	0.7143	0.0459
Olive-sided flycatcher	0.9492	0.2887
Nuthatch *spp*[d]	0.9912	0.4466
American robin whinny	0.4375	0.0617
Canada goose	0.9908	0.7652
Mourning dove	0.7444	0.7319
Chipmunk *spp* chirp[e]	0.9609	0.8809
American pika	0.8750	0.4375
Douglas' squirrel rattle	0.9833	0.8224
Douglas' squirrel chirp	0.9645	0.7716
Dog barking	0.9380	0.2893
Insect buzz	0.9881	0.1237
Frog chorus	0.9917	0.8354
Human speech	0.9435	0.7086
Yarder machine	0.9080	0.7662
Gunshot	0.1818	0.1000

[a] NSO and barred owl
[b] Red-breasted, Williamson's, and red-naped sapsuckers
[c] Black-capped, chestnut-backed, and mountain chickadees
[d] Red-breasted and white-breasted nuthatches
[e] Townsend's and yellow-pine chipmunks

Table 2. The number of autonomous recording unit stations deployed during 2022 in designated Wilderness Areas administered by US Forest Service or US National Park Service.

Wilderness Area	Study Area	Number of Stations
Alpine Lakes Wilderness	CLE	4
Boulder Creek Wilderness	UMP	1
Buckhorn Wilderness	OLY	9
Colonel Bob Wilderness	OLY	8
Cummins Creek Wilderness	COA	3
Daniel J. Evans Wilderness[a]	OLY	235
Devils Staircase Wilderness	COA	16
Drift Creek Wilderness	COA	2
Goat Rocks Wilderness	GIP	8
Indian Heaven Wilderness	GIP	2
Menagerie Wilderness	HJA	4
Mount Jefferson Wilderness	HJA	1
Mount Rainier Wilderness[a]	RAI	96
Mount Skokomish Wilderness	OLY	4
Mount Washington Wilderness	HJA	2
Mountain Lakes Wilderness	CAS	5
Phillip Burton Wilderness[a]	MAR	7
Rock Creek Wilderness	COA	1
Rogue-Umpqua Divide Wilderness	CAS	10
Sky Lakes Wilderness	CAS	63
The Brothers Wilderness	OLY	4
Three Sisters Wilderness	HJA	30
Trinity Alps Wilderness	NWC	11

[a] Administered by US National Park Service

Table 3. The number of hexagons and stations surveyed using passive acoustics monitoring in each study area during 2018–2022 within in the Northwest Forest Plan Area. Unless noted, surveys were conducted with Song Meter SM4 autonomous recording units. COA = Oregon Coast Range, OLY = Olympic Peninsula, KLA = Klamath, CLE = Cle Elum, TYE = Tyee, HJA = H.J. Andrews Experimental Forest, CAS = South Cascades, NWC = Northwest California, MAR = Marin County, RAI = Mt. Rainer NP, GIP = 2% Gifford Pinchot National Forest, UMP= 2% Umpqua national forest

Study area	Number of hexagons					Number of stations				
	2018	2019	2020	2021	2022	2018[a]	2019	2020	2021	2022
COA	120	106	120	120	117	577	412[b]	473[c]	476	466
OLY	88	120	119	119	120	435	472	464	472	474
KLA		63	73	73	73		244	290[d]	276	292
CLE			69	75	75			267[e]	298	300
TYE				40	40				155	160
HJA				70	70				279	280
CAS				98	98				380	391
NWC				30	30				120	119
MAR				7	7				26	27
RAI				11	24				43	96
GIP					23					91
UMP					13					52
TOTAL	208	289	381	643	690	1,012	716	464	2,525	2,748

[a] During 2018 survey design was five stations per hexagon.
[b] 49 SWIFT units used in addition to SM4s.
[c] 66 SWIFT units and 95 Song Meter Minis used in addition to SM4s.
[d] 43 Song Meter Minis used in addition to SM4s.
[e] 15 Song Meter Minis used in addition to SM4s.

Table 4. The number of hours of sound data collected in each study area and processed for automated species identification with a trained convolutional neural network. COA = Oregon Coast Range, OLY = Olympic Peninsula, KLA = Klamath, CLE = Cle Elum, TYE = Tyee, HJA = H.J. Andrews Experimental Forest, CAS = South Cascades, NWC = Northwest California, MAR = Marin County, RAI = Mt. Rainer NP, GIP = 2% Gifford Pinchot National Forest, UMP= 2% Umpqua national forest

Study area	2018[a]	2019	2020	2021	2022
COA	200,036	154,936	190,312	215,495	261,000
OLY	148,015	163,227	219,026	214,841	264,499
KLA		89,748	130,122	133,461	162,192
CLE			104,651	153,590	152,344
TYE				77,013	92,574
HJA				131,239	149,877
CAS				177,723	188,271
NWC				47,971	53,706
MAR				11,001	10,199
RAI				11,204	50,469
GIP					58,630
UMP					29,990
TOTAL	348,051	407,911	644,111	1,162,538	1,473,751

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

Table 5. Estimated number of detections for 48 sound classes (36 wildlife species) from bioacoustics data by study area in 2022 based on output from the fourth version of PNW-Cnet (PNW-Cnet v4). Spotted owl and marbled murrelet counts are validated counts. Estimated detections for other sound classes were calculated as the number of 12 s clips in the audio dataset to which the PNW-Cnet v4 assigned a score exceeding 0.95 for that class, multiplied by the precision estimate (Table 1). 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.

Sound	CAS (n=391)	CLE (n=300)	COA (n=466)	GIP (n=118)	HJA (n=280)	KLA (n=292)	MAR (n=27)	NWC (n=119)	OLY (n=474)	RAI (n=96)	TYE (n=160)	UMP (n=52)
Northern spotted owl location call - MALE[a]	1413	9	17	0	583	499	983	678	881	0	1	22
Northern spotted owl location call - FEMALE[a]	10	1	8	0	68	193	57	25	6	0	0	0
Northern spotted owl location call - UNKNOWN[a]	4616	379	105	0	1590	1388	4186	1719	1664	2	90	123
Northern spotted owl series call[a]	916	1	14	0	164	283	4538	269	308	0	4	0
Marbled murrelet keer call[b]	0	0	3924	0	0	0	0	0	3934	43	7	1
American pika	604	2655	64	283	1232	128	4	20	59	70	25	8
American robin whinny call	11765	6753	16296	1150	6346	11505	1345	4389	18616	231	6461	2300
Strix owl contact whistle[c]	137	86	517	9	274	793	681	36	258	16	175	6
Band-tailed pigeon	2963	687	419199	3056	16588	89025	21626	9062	96822	1853	89640	4416
Barred owl eight-note call	11290	11015	70242	9239	34895	26833	102	3547	40007	8792	28781	2947
Barred owl inspection call	11853	9426	38255	9855	15780	20452	281	2641	13559	4451	20685	1368
Barred owl series call	2860	1827	19960	2182	5238	5703	41	1142	6196	821	7870	398
Canada goose	38143	5163	16042	33	3807	16152	238	514	1640	23	7337	519
Canada jay (gray jay)	4686	5826	23668	5615	8610	3783	607	697	26134	8332	6123	1791
Chickadee song[d]	5452	8564	62	4	204	254	13	157	55	121	57	9
Chipmunk chirp call[e]	134992	86910	59688	40954	56532	90919	1225	14710	38581	40044	56971	15878
Common nighthawk call	167095	11074	29327	49578	47469	20715	10	7412	60830	304	14255	7832
Common nighthawk dive	115759	4946	11588	18965	24375	14992	8	2870	12872	19	16174	1799
Common poorwill	31136	39402	155	15	54	15285	62	15785	75	10	210	516
Common raven	132995	98547	251156	24637	57328	214452	59870	39980	108205	4246	141117	12327
Dog barking	3605	2773	5734	169	341	50476	2431	5110	2867	20	14484	1593

Douglas' squirrel chirp	171234	101581	35045	25535	39349	20690	49	29794	49709	5615	14983	3865
Douglas' squirrel rattle	133352	118226	38673	23504	36012	28540	161	28316	78414	4382	26224	2759
Downy woodpecker call	3	19	6	9	17	26	0	19	22	2	3	16
Flammulated owl	4869	175982	212	326	1723	1151	41	67103	163	1	402	332
Frog chorus	1060338	515978	351602	143446	347229	809932	102649	235524	328247	786	352805	31377
Great horned owl	68905	96715	7785	3725	3661	34321	21202	2368	12351	193	19831	6874
Gunshot	555	709	896	138	236	417	27	101	686	29	228	121
Hermit thrush	1679920	994794	22467	478212	835392	1268343	1266	79267	226351	220413	553263	143850
Human speech	511	543	1112	196	1030	468	1038	123	2039	905	333	467
Insect buzz	361131	158570	154486	183762	197786	208115	3028	54993	314109	107302	108960	43686
Mountain quail	28513	518	21259	129	7519	292336	128	92108	511	92	41086	14987
Mourning dove	2783	564	3459	3	257	27999	11351	11231	374	0	3576	38
Northern pygmy-owl	67369	37206	618858	6686	48284	275391	171	166352	74226	7503	166031	31187
Northern saw-whet owl	205224	69392	262821	3446	25341	175384	46899	97416	26683	2527	111188	11793
Northern flicker series call	259301	69811	58527	6752	61652	230431	6408	73629	21034	1867	104615	29143
Nuthatch[f]	2753025	1544873	480960	485507	990647	953900	15804	306866	642535	315598	373504	131099
Olive-sided flycatcher	95467	50666	4731	28641	22523	34683	533	29278	18044	4671	18975	10549
Pileated woodpecker call	29998	6565	40056	1625	11953	48964	5399	8606	16916	294	27062	3270
Sapsucker drum[g]	18	3	12	9	4	2	0	10	0	0	63	3
Sooty grouse	175246	253489	62275	28548	289888	331211	0	14048	1117561	47528	571971	157742
Spotted towhee	1884	15	1964	0	243	3085	692	1795	26	0	1712	224
Steller's jay	275969	38469	390356	25745	183977	570535	56458	228372	127189	10330	186182	57780
Swainson's thrush	75853	90142	4843147	228460	753445	160593	475	16822	184492	17102	381728	74793
Varied thrush	21510	414049	958608	340070	394118	6838	275	611	1994466	575501	115789	12274
Western screech-owl	5325	5511	113398	495	5731	335657	457	42836	4171	43	152414	1085
Woodpecker drum[c]	3593	2300	4229	94	1362	3159	742	1875	3065	123	1653	1359
Wrentit	1226	243	167194	146	188	176887	30418	6962	384	48	28005	330
Yarder	108	36	81164	158	11248	70749	28	11	3259	669	37515	428

[a] Count of human validated detections from full review of 0.25 threshold.

[b] Number of validated detections from partial review of 0.95 threshold to confirm presence at the weekly station level.

[c] N. spotted owl and barred owl

[d] Black-capped, chestnut-backed, and mountain chickadees

[e] Townsend’s and yellow-pine chipmunks
[f] Red-breasted and white-breasted nuthatches
[g] Red-breasted and Williamson’s sapsuckers

Table 6. Proportion of autonomous recording unit hexagons and stations with validated detections of northern spotted owl for years that surveys were conducted in 2018–2022 within the Northwest Forest Plan Area.

	Hexagon					Station				
Study area	2018	2019	2020	2021	2022	2018	2019	2020	2021	2022
COA	0.18	0.13	0.10	0.15	0.09	0.07	0.06	0.04	0.07	0.04
OLY	0.16	0.18	0.24	0.20	0.27	0.06	0.08	0.12	0.10	0.12
KLA		0.43	0.53	0.48	0.44		0.27	0.34	0.31	0.23
CLE			0.19	0.17	0.11			0.06	0.08	0.07
CAS				0.34	0.27				0.21	0.16
HJA				0.46	0.39				0.25	0.23
MAR				0.95	1.00				0.88	0.93
NWC				0.77	0.73				0.56	0.55
RAI				0.09	0.02				0.02	0.04
TYE				0.35	0.20				0.17	0.08
GIP					0.00					0.00
UMP					0.54					0.21

Table 7. Proportion of autonomous recording unit hexagons and stations with validated detections of marbled murrelet for years that surveys were conducted in 2018–2022 within the Northwest Forest Plan Area.

	Hexagons					Stations				
Study area	2018	2019	2020	2021	2022	2018	2019	2020	2021	2022
COA	0.83	0.75	0.79	0.82	0.86	0.71	0.61	0.60	0.68	0.74
OLY	0.78	0.85	0.84	0.87	0.85	0.60	0.70	0.63	0.70	0.71
KLA		0.00	0.00	0.01	0.00		0.00	0.00	<0.01	0.00
CLE			0.00	0.00	0.00			0.00	0.00	0.00
CAS				0.00	0.00				0.00	0.00
HJA				0.00	0.00				0.00	0.00
MAR				0.00	0.00				0.00	0.00
NWC				0.00	0.00				0.00	0.00
RAI				0.09	0.08				0.07	0.13
TYE				0.15	0.10				0.05	0.03
GIP					0.00					0.00
UMP					0.08					0.02

11. Figures

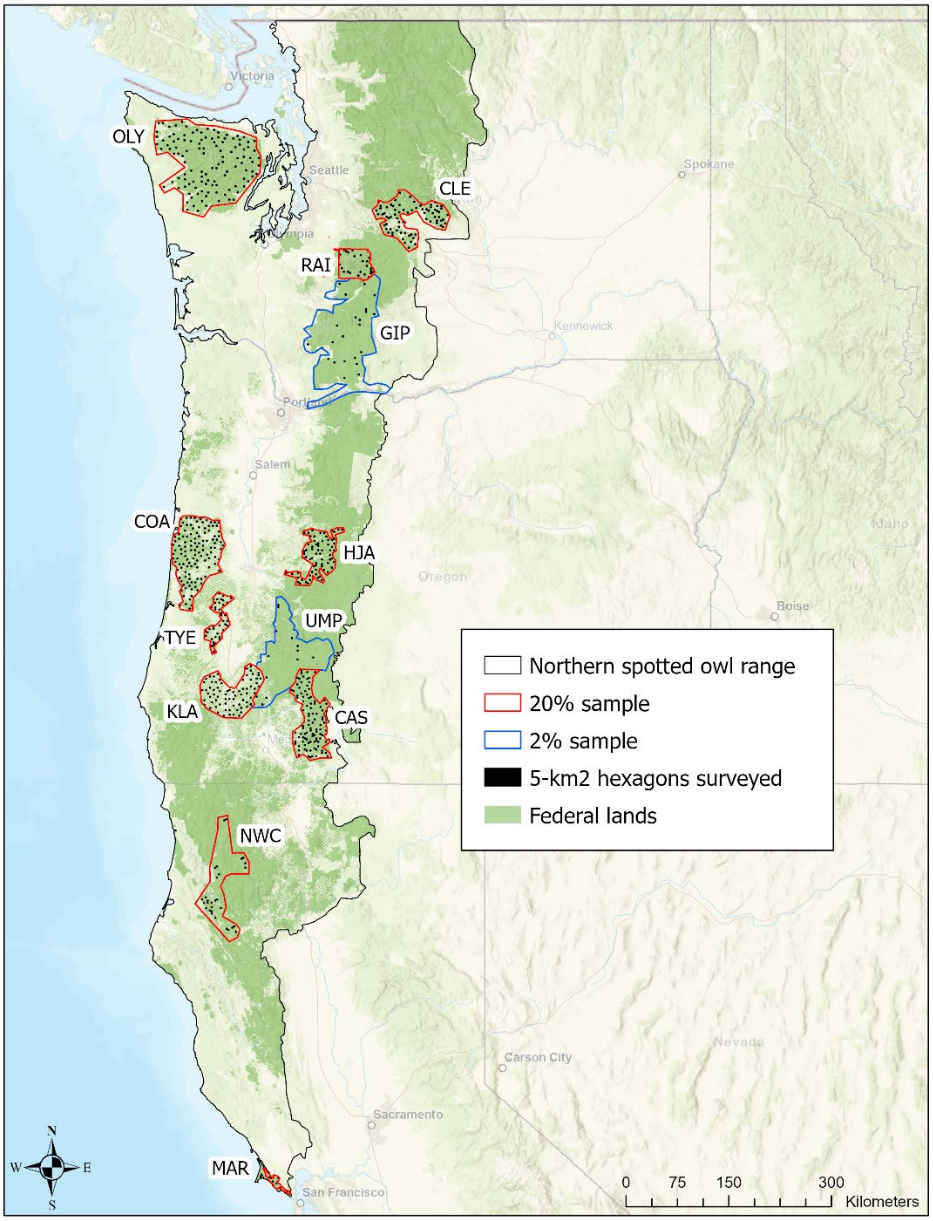


Figure 1. Locations of 5 km^2 hexagons (n = 690) surveyed in 12 study areas using passive acoustic monitoring. All 20% sample study areas overlapped with historical northern spotted owl demographic study areas. Study areas: OLY = Olympic Peninsula, CLE = Cle Elum, RAI = Mt. Rainer National Park, COA = Oregon Coast Range, HJA = HJ Andrews, TYE = Tyee, KLA = Klamath, CAS = South Cascades, NWC = Northwest California, and MAR = Marin County. UMP= Umpqua National Forest, GIP = Gifford Pinchot National Forest.

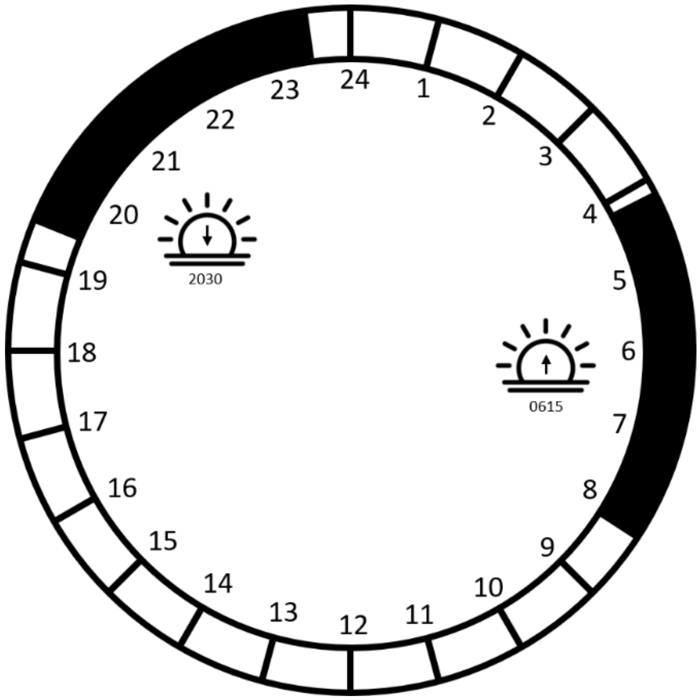


Figure 2. Example 24 h diel cycle (sunrise at 0615, sunset at 2030) recording schedule used on autonomous recording units to conduct passive acoustic monitoring within the Northwest Forest Plan area. Recording times shown with black bars occurring during 4 h blocks during crepuscular period and 10 minutes 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.

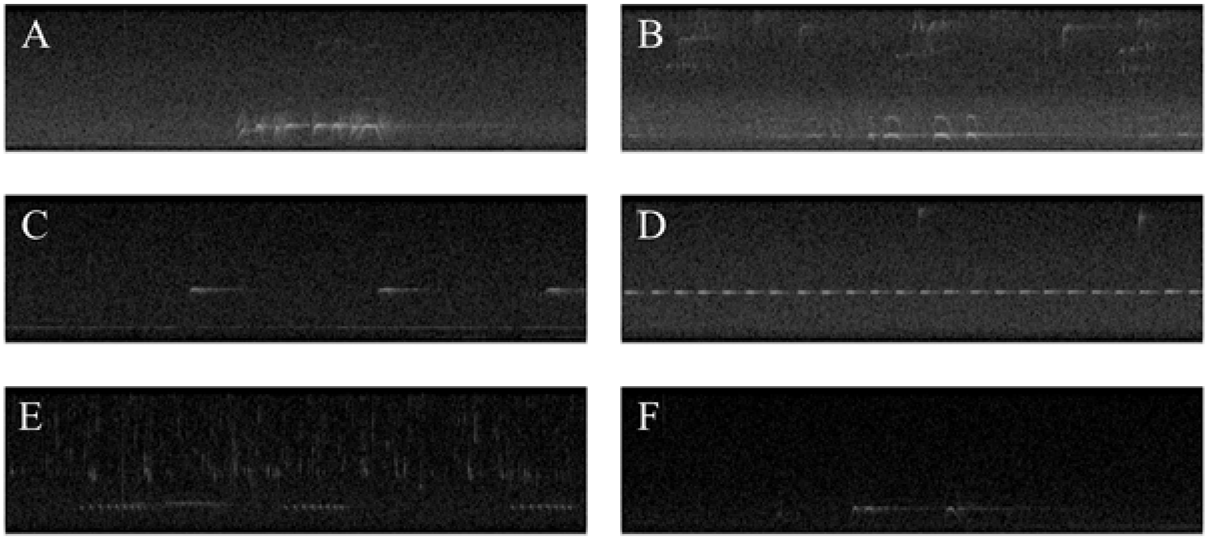
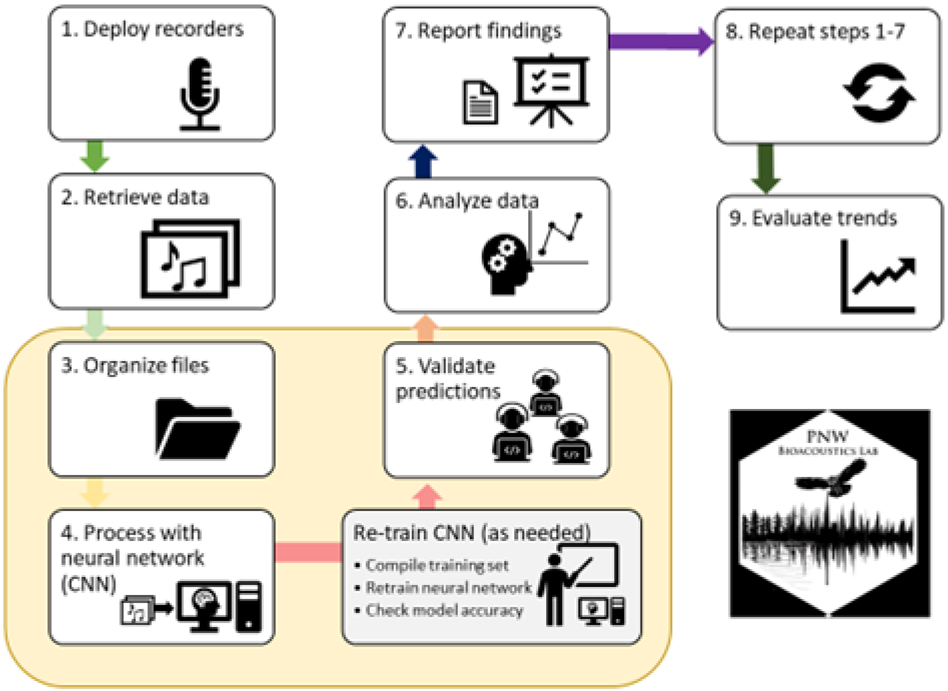
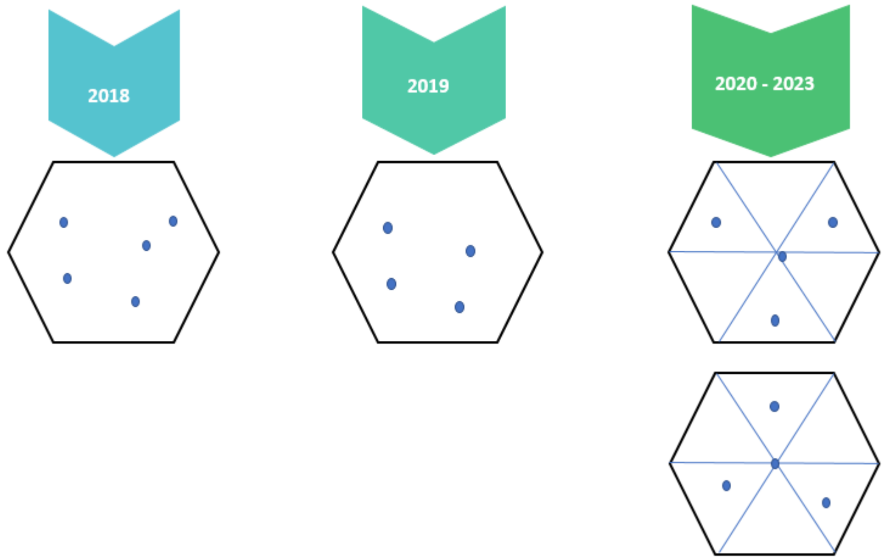


Figure 3. Example spectrogram images of target species calls used by Ruff et al. (2020) to train a convolutional neural network (PNW-Cnet) to detect owl calls in field recordings. A = barred owl, B = great horned owl, C = northern pygmy owl, D = northern saw-whet owl, E = western screech owl, F = northern 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.

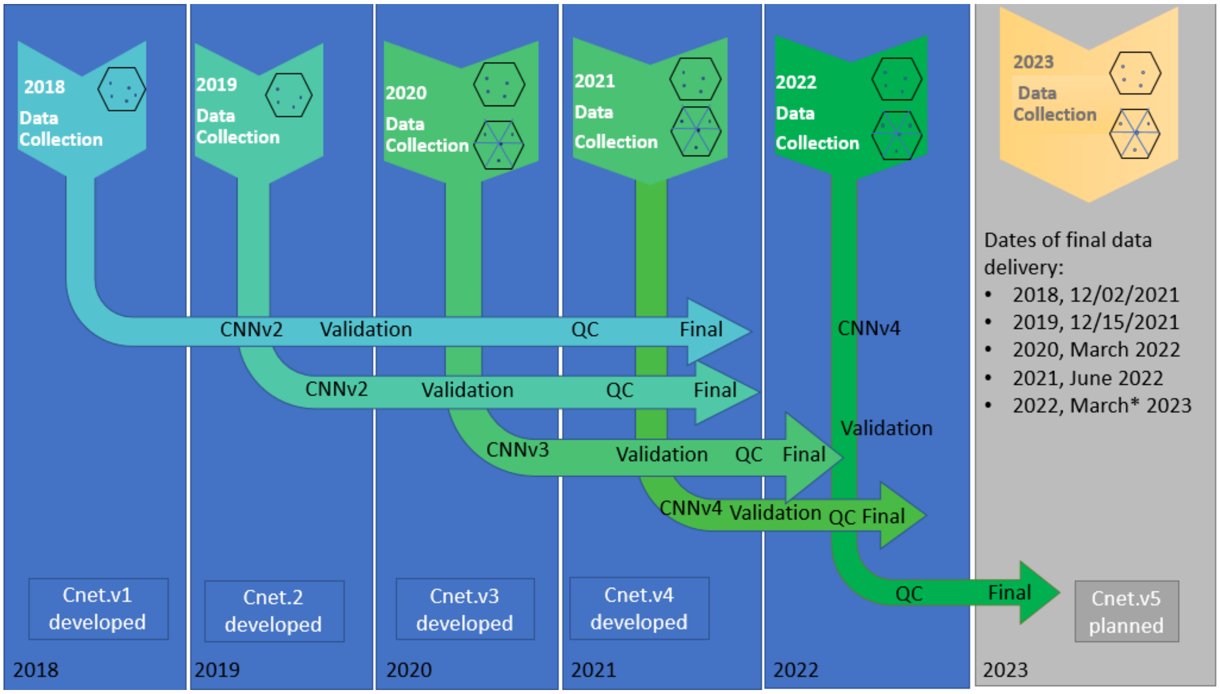
12. Appendices



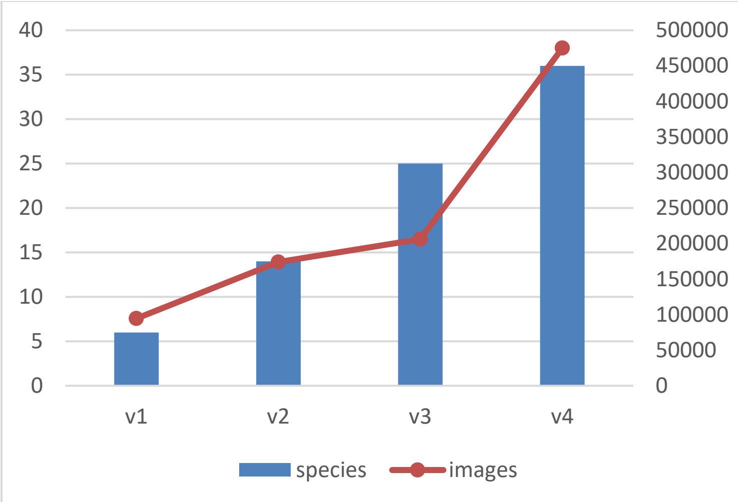
Appendix A. Workflow for the passive acoustic monitoring program within the Northwest Forest Plan area. The process includes data collection, training the convolutional neural network (PNW-Cnet) for automated species identification, processing data, analyzing data, and reporting findings. Highlighted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



Appendix B. 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 were still applied, thus some stations needed to be adjusted to meet rule set requirements.



Appendix C. Timeline of data collection, versions of convolutional neural network (CNNv2 = PNW-Cnet v2, CNNv3 = PNW-Cnet v3, CNNv4 = PNW-Cnet v4) used, status of validation.



Appendix D. Convolutional neural network version (v1 = PNW-Cnet v1, v2 = PNW-Cnet v2, v3 = PNW-Cnet v3, v4 = PNW-Cnet v4), number of species (primary y-axis) and sample size of images in model training set (secondary y-axis).