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RESEARCH ARTICLE

Passive acoustic monitoring is a cost-effective approach to conduct inland surveys for marbled murrelets

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Abstract

The marbled murrelet (*Brachyramphus marmoratus*) is a seabird of conservation concern that nests in late-successional, old-growth forests in Oregon, Washington, and California, USA. Traditional audio-visual surveys have been the standard method for detecting murrelets in forests. Given that murrelets can be extremely cryptic in forest environments, audio-visual surveys are difficult, time consuming, and expensive to conduct. Passive acoustic monitoring (PAM) may be a useful and cost-effective alternative. Using a paired murrelet survey design, we compared detection probabilities across 88 survey points in forests of Oregon and Washington. We conducted 2–4 early morning audio-visual surveys and 13–53-day PAM surveys from 14 June through 5 August 2022 and 2023, when murrelets typically make the most frequent inland flights during the nesting season. We found the average detection probability for murrelets on any given day was higher for an audio-visual survey visit (0.40, SD = 0.17) than for a PAM survey day (0.19, SD = 0.10). However, the cumulative detection probability for PAM surveys was 0.98 (95% CI = 0.96–1.0) after 19 survey days, whereas the same cumulative detection probability would require 9 audio-visual survey visits. Using simulations to compare the cost-effectiveness of both methods, we found audio-visual surveys cost more when compared with PAM surveys in 61–91% of scenarios because they require specialized personnel training and additional pre-dawn visits. Further, PAM per survey costs decreased as the number of survey days per point increased and over time after initial costs were incurred, particularly when autonomous recording units were reused for multiple years. While audio-visual surveys are the standard method for murrelet surveys in forest habitats, PAM represents a more cost-effective approach to determine the presence of murrelets.

KEYWORDS

audio-visual surveys, autonomous recording units, bioacoustics, *Brachyramphus marmoratus*, convolutional neural networks, Northwest Forest Plan

The marbled murrelet (*Brachyramphus marmoratus*; hereafter murrelet) is a small seabird in the Alcid family that occurs along the Pacific coastline from the Aleutian Islands of Alaska to central California, USA. Unlike most seabirds, murrelets spend most of their time foraging in near-shore ocean environments but migrate inland up to 80 km to nest in late-successional and old-growth forests with suitable nesting structures (Hull et al. 2001). Murrelets were listed as a federally threatened species in 1992 due to threats to nesting habitat from timber harvest, forest fires, and stressors at sea such as limited prey resources, water pollution, and gillnetting (Department of Interior Fish and Wildlife Service 1992, U.S. Fish and Wildlife Service 1997). Murrelets were also listed as state-endangered in California, Washington, and Oregon in 1992, 2016, and 2021, respectively (Desimone 2016, Oregon Department of Fish and Wildlife 2021, California Natural Diversity Database 2025). Moreover, murrelets are a focal species for monitoring the effectiveness of the Northwest Forest Plan, which guides management on approximately 10 million ha of federally managed forests in the Pacific Northwest, USA (Forest Ecosystem Management Assessment Team 1993, Madsen et al. 1999).

Due to the murrelet's conservation status and reliance on older forests with suitable nesting habitat, murrelet surveys are frequently required prior to the implementation of planned forest management activities where such activity may cause harm to occupied murrelet nesting habitat or otherwise disrupt breeding behaviors (Evans Mack et al. 2003, Pacific Seabird Group 2024). Specifically, replicate (primarily spatial replicates) audio-visual surveys are conducted at dawn in and adjacent to proposed management project areas to record visual and aural detections of murrelets as they fly above or through forest stands. Although murrelets are solitary nesters, they exhibit vocalizations while flying inland and prospecting for nest sites and have been reported to make quieter calls in and around nests (Nelson and Peck 1995, Cragg et al. 2015, Valente et al. 2021). Occupied behaviors are visual observations of murrelets circling overhead, flying below canopy, and landing in trees, and are generally assumed to be reliable indications of murrelet nesting activity (Evans Mack et al. 2003, Pacific Seabird Group 2024). Forest stands where occupied behaviors are documented are usually classified as occupied within a regulatory framework and the proposed management activities are altered. A high number of audio-visual survey detections represent auditory-only detections (74–88%; Rodway et al. 1993, Ralph et al. 1995) which result in forest stands being classified as only having murrelet presence, since no occupied behaviors were documented to further classify the stand as occupied. Until the 2024 revision of the Marbled Murrelet Inland Survey Protocol (Pacific Seabird Group 2024), presence classification did not afford protection status. Audio-visual surveys can be logistically challenging, given that murrelets can be exceptionally cryptic when making inland flights, views of the sky in older forests can be restricted, murrelets are frequently active during low-light hours of pre-dawn, environmental noise and weather can affect surveyors' ability to observe bird locations, and surveyors can only survey a single location per day.

Audio-visual surveys also require substantial resources, have site-specific limitations for observing murrelets, and likely result in birds going undetected (Valente et al. 2024). Still, audio-visual surveys are conducted annually across broad spatial scales to inform management decisions (Betts et al. 2020, Valente et al. 2023, Baumbusch et al. 2025).

Costs associated with visiting survey points are a significant factor when conducting murrelet audio-visual surveys because the survey protocol requires multiple visits to a project area to determine if the project area should be classified as unoccupied. According to the current murrelet audio-visual survey protocol, a project area can now be classified as occupied using a presence-only approach that uses both visual and auditory murrelet detections or an occupancy approach based on visual observations of occupied behaviors (Pacific Seabird Group 2024). When using a presence-only approach, the protocol requires 3 separate days with murrelet detections to determine occupancy, or 8 surveys are necessary to achieve a false omission rate ≤ 5%, which is the probability that a project area is occupied but classified as not occupied. For the occupancy approach, a single visual observation of murrelets exhibiting occupied behaviors is needed to determine occupancy, or 12 visits would be required to achieve a false omission rate ≤ 5% (Pacific Seabird Group 2024 Springford and Jones, Pacific Seabird Group, unpublished report). When done at scale, both options under the protocol require up to 8–12 survey visits at a project area over a 2-year period to meet monitoring requirements.

Passive acoustic monitoring (PAM) is an alternative option for monitoring vocal species of multiple taxa, including bats, birds, marine mammals, terrestrial mammals, and amphibians (Hutter and Guayasamin 2015, Klingbeil and Willig 2015, Sugai et al. 2019, López-Baucells et al. 2021, Tosa et al. 2021). Although PAM can have a large initial financial investment, the approach requires fewer field technicians for the deployment and retrieval of equipment and can cover a much larger area than other, more intensive survey methods (Lesmeister and Jenkins 2022, Duarte et al. 2024). Others have compared the detectability of murrelets using audio-visual survey data collected by trained field crews and PAM survey data collected by autonomous recording units (ARUs). Borker et al. (2015) conducted 31 audio-visual surveys within 10 m of an ARU at 7 survey points and found human observers conducting audio-visual surveys detected more murrelets per morning, but that PAM had more murrelet detections across the season due to a greater number of days ARUs were operational. On the other hand, Cragg et al. (2016) conducted 12 audio-visual surveys within 300 m of an ARU and found similar mean counts of detections between the 2 survey methods. Although the studies had mixed success, both were conducted before computational advances in convolutional neural networks (CNNs).

Convolutional neural networks have evolved extensively over the years. Biologists can use CNNs to efficiently process large amounts of visual data, including photo identification of plants and animals and identification of sounds using spectrograms (Rzanny et al. 2017, Gu et al. 2018). It is now more manageable to collect millions of hours of sound data and convert those data to spectrograms to accurately identify vocalizations of focal species using open-source CNN models (Ruff et al. 2019, 2021, 2023; Zhong et al. 2021).

Duarte et al. (2024) demonstrated how PAM and CNNs can be used to quantify the intensity of murrelet habitat use across forest landscapes. As such, our objectives were to quantify and compare murrelet detection probabilities and the associated cost between data collected via audio-visual and PAM surveys coupled with CNNs. Based on the findings of previous studies (Borker et al. 2015, Cragg et al. 2016, Duarte et al. 2024), we predicted detection probability per survey would be higher when conducting audio-visual surveys. However, like Borker et al. (2015), we predicted that we would be more likely to detect murrelets at a survey point across the season using PAM surveys due to the feasibility of long-duration deployments of ARUs. Finally, we predicted PAM surveys, when done at scale (i.e., across multiple survey points) and with the aid of a CNN, would lead to a much lower financial cost compared to audio-visual surveys.

STUDY AREA

We conducted surveys in Washington and Oregon, USA (Figure 1). In Oregon, we conducted surveys on lands managed by the Oregon Department of Forestry across the Tillamook and West Oregon Districts. The survey points in the Tillamook District were dominated by western hemlock (*Tsuga heterophylla*), Douglas-fir (*Pseudotsuga menziesii*), Stika spruce (*Picea sitchensis*), and small components of western redcedar (*Thuja plicata*). The average stand age was 110 years old. The survey points in the West Oregon District were dominated by Douglas-fir, western hemlock, and big-leaf maple (*Acer macrophyllum*), and the average stand age was 157 years old. We calculated the stand age on the state-managed lands in Oregon using Oregon Department of Forestry Stand Level Inventory annual reports (State of Oregon 2024). In Washington, we conducted surveys at Naval Radio Station Transmitter, Jim Creek, within an area covered by 744 ha of old-growth (800–1500 years) and second growth (60–90 years) forest dominated by western hemlock, western redcedar, red alder (*Alnus rubra*), Douglas-fir, and Sitka spruce. Naval Radio Station Transmitter, Jim Creek is managed by the U.S. Navy as a radio transmitter facility and recreational area (Wagoner et al. 2018, DeHaan 2019). The study areas were purposely chosen because both were historically occupied by murrelets based on survey data from 1993–2017 and because our objectives for our study focused on understanding detectability of murrelets, conditional on them being present. Given our study objectives, the site selection criteria did not influence our inferences other than to help ensure murrelets were likely present to estimate detection probabilities.

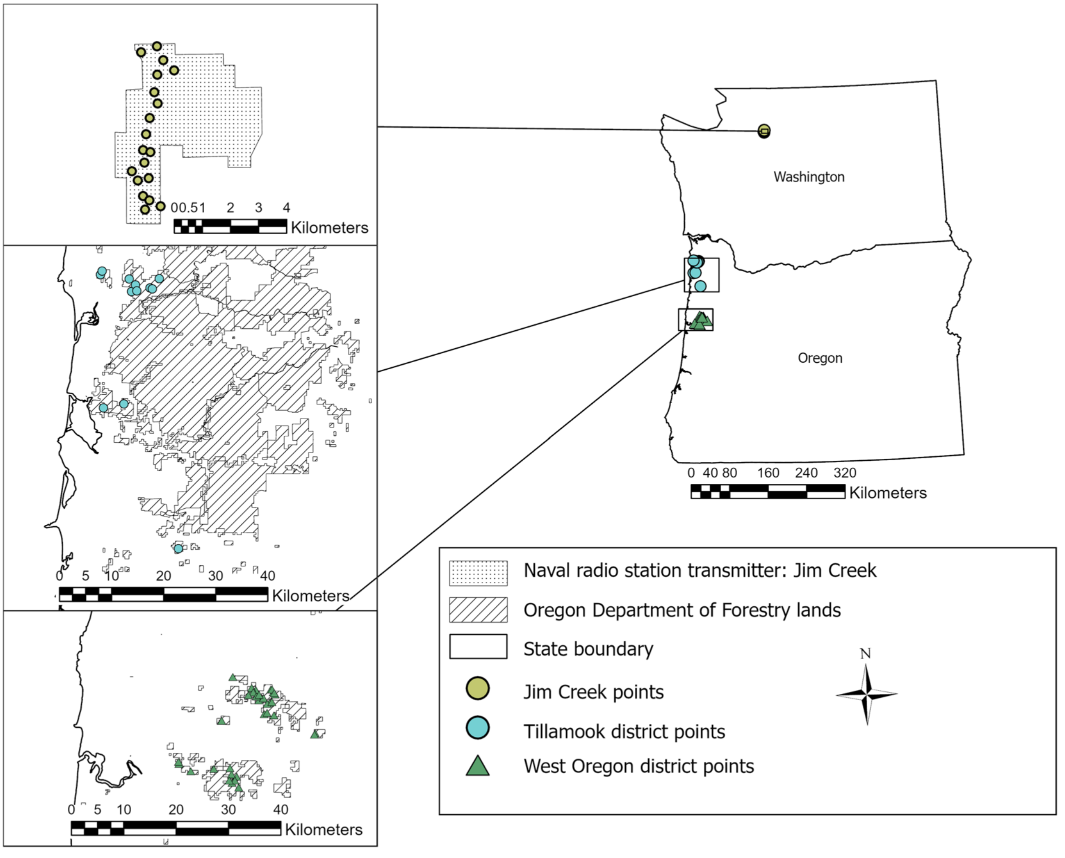

FIGURE 1 Point locations of surveys conducted 14 June–5 August 2022 and 2023 for marbled murrelet (*Brachyramphus marmoratus*) on lands managed by the U.S. Navy in Washington, USA, at the Naval Radio Station Transmitter, Jim Creek (n = 19 unique points in both years) and Oregon Department of Forestry in Oregon (ODF) across 2 districts, Tillamook and West Oregon (n = 25 unique points each year).

METHODS

Audio-visual surveys

During the summers of 2022 and 2023, we conducted audio-visual surveys at 38 points (19 unique point locations surveyed in both years) in Washington and 50 points (25 unique point locations surveyed each year) in Oregon. We established points within or in nearby mature forests with nesting platform structures and old-growth forests along trails and roads, which maximized safety of our field crew, given that audio-visual surveys require pre-dawn hiking to remote points in dense and steep forests. Following the Marbled Murrelet Inland Survey Protocol, we conducted audio-visual surveys in openings of the forest canopy (Evans Mack et al. 2003, Pacific Seabird Group 2024). We conducted audio-visual surveys starting 45 minutes before sunrise until 75 minutes after sunrise or 15 minutes after the last detection, and we completed 2–4 ($\bar{x}$ = 3.34, SD = 0.52) replicate surveys per year at each point. We randomized the order in which points were surveyed while considering logistical constraints and temporal coverage to ensure each point was surveyed in early and late seasons. All audio-visual surveys took place from 14 June through 5 August, which included peak inland murrelet activity (Jodice and Collopy 2000). Furthermore, all observers were trained, tested, and certified through a standardized 4–5-day training course following the 2003 Marbled Murrelet Inland Survey Protocol (Evans Mack et al. 2003). We included both visual and auditory detections from audio-visual surveys in our analysis. Each morning survey was given a binary detection (1) or nondetection (0) designation.

Passive acoustic monitoring surveys

We deployed ARUs within 10–50 m of audio-visual survey points. We used Song Meter (SM) 4 or SM Mini ARUs (Wildlife Acoustics Inc. 2022), which are fully enclosed, weather-proof, programmable, and suitable for long-duration deployments. The SM4 has 2 built-in omnidirectional microphones with a signal-to-noise ratio of 80db typical at 1 kHz with sensitivity at −35 ± 4 db. The SM Mini is a smaller unit that has one built-in omnidirectional microphone with a signal-to-noise ratio of 78 dB typical at 1 kHz. On both recording setups, we recorded in mono, which saves recording and computing space. For the SM4s, we recorded on the right channel and set the gain and pre-amp gain to the default settings 16.0 dB and 26 dB, respectively, and high pass filter to 220 Hz. On the SM Mini units, we recorded on the left channel and set the gain to the default 18db. The sample rate was set to 32 kHz, and the max recording length was set to 60 min for both recorder types. Four D-cell alkaline batteries were used in each SM4, and 4 AA non-rechargeable lithium batteries were used in each SM Mini. With the recording schedule we used and battery configuration for each unit type, the SM Mini recorded approximately 21–25 days and the SM4 recorded over 43 days. Batteries were replaced in the SM Minis every 21 days. We used a 256 GB secure digital card, class 4 or greater, in each ARU and found it had sufficient storage for our recording schedule and duration of deployment. We programmed ARUs to record during crepuscular periods at sunrise (2 hours before to 2 hours after) and sunset (1 hour before to 3 hours after), and 10 minutes at the top of each hour during day and night. The sunrise recording schedule ensured that we overlapped the same survey window as the early morning audio-visual surveys. At each point, we mounted ARUs to small trees (15–20 cm diameter at breast height) to allow microphones to extend past the main trunk for unobstructed recording. Autonomous recording units recorded from 13–53 days ($\bar{x}$ = 39.97, SD = 9.24). Passive acoustic monitoring surveys at each point required 2 field visits, for the deployment and retrieval of the equipment, except where batteries needed to be replaced for the SM minis.

Audio data processing

We implemented a multi-step workflow that integrated PNW-Cnet, a well-developed CNN for the Pacific Northwest, USA, to efficiently process large volumes of audio data for murrelets, combining semi-automated identification and human validation (Ruff et al. 2019, 2021, 2023). PNW-Cnet is an open-source product with user-friendly tools that can be used to analyze sound data. In 2022, we used PNW-Cnet v4, which had a precision of 0.987 and a recall of 0.914 (Ruff et al. 2023). In 2023, we used the updated PNW-Cnet v5, which had a precision of 0.991 and a recall of 0.926 (Lesmeister et al. 2025). Precision is defined as a ratio of true positives to apparent detections, or a proportion of real detections. Recall is the ratio of true positives to the number of test images that contained the class. We set the confidence score threshold to 0.95, and PNW-Cnet produced review files containing all the apparent detections of murrelet calls from the wav files that met the threshold. We then used Kaleidoscope Pro (Wildlife Acoustics Inc. 2024) to validate potential murrelet detections (i.e., 12 second clips with a confidence score threshold of ≥0.95 for the murrelet keer call class). Human observers validated all daily murrelet detections meeting the confidence score threshold regardless of when the detection occurred for that day. We used only human-validated murrelet keer calls to develop daily binary detection and nondetection encounter histories.

Background noise has consistently been found to be an important predictor of detection probabilities when analyzing PAM data (Duchac et al. 2020, 2021; Appel et al. 2023; Rugg et al. 2023; Weldy et al. 2023) and can influence the number of murrelet keer call detections (Duarte et al. 2024). Therefore, we used the sound pressure level analysis feature in Kaleidoscope Pro to quantify background noise levels at each survey point (Table 1). We then produced the mean daily noise levels per point. Importantly, the noise value is a negative number and is measured as decibels below full scale (dBFS), with smaller values indicating a quieter environment. We calculated noise values for days that corresponded with both audio-visual and PAM surveys.

Statistical analyses

We fit single-season occupancy models (MacKenzie et al. 2018) using program R (v4.4.0; R Core Team 2024) with packages unmarked 1.4.1 (Fiske and Chandler 2011, Kellner et al. 2023) and MuMIn 1.47.5 (Bartoń 2023). Our

TABLE 1 Summary statistics for explanatory variables included in the global models for occupancy (ψ) and detection probability (*p*) for analysis of marbled murrelet (*Brachyramphus marmoratus*) survey data collected in Washington and Oregon, USA, 2022–2023.

Parameter	Variable	Description	Summary
p	Day of year	165 = June 14; 217 = August 5	Min–Max = 165–217 $\bar{x}$ (SD) = 191.14 (13.28)
p	Temperature	Daily minimum temperature in Celsius collected from nearest local weather stations	Min–Max = 5.4–16.9 $\bar{x}$ (SD) = 11.53 (1.84)
p	Noise	Mean daily background noise levels measured as decibels below full scale (dBFS)	Min–Max = −120.13–−71.37 $\bar{x}$ (SD) = −106.86 (6.17)
p	Survey method	Audio-visual; Passive Acoustic Monitoring (PAM)	Audio-visual: 294 PAM: 3,517
ψ	Study area	Naval Radio Station Transmitter: Jim Creek; Oregon Department of Forestry: Tillamook District and West Oregon District	Jim Creek: 38 Tillamook District: 12 West Oregon District: 38
ψ	Year	Survey year	2022: 44 (Jim Creek: 19, Tillamook: 7, West Oregon: 18) 2023: 44 (Jim Creek: 19, Tillamook: 5, West Oregon: 20)

objectives were focused on factors affecting detection probability and we were not interested in trends in occupancy. Therefore, we assumed independence between years such that year 1 occupancy estimates were not used to inform year 2 occupancy estimates (MacKenzie et al. 2018). We stacked our encounter histories by point and year, creating a point-year combination for each location and included year as a covariate on occupancy (ψ). We estimated occupancy (ψ) and detection probability (p), where occupancy probability is the probability that a survey point was used by at least one murrelet, and detection probability is the probability that a murrelet was detected during a survey given a survey point was used by a murrelet. Given that murrelets fly inland for prospecting, nesting, and feeding young and that we included auditory detections in our data, our occupancy parameter could be interpreted as site use and is equivalent to the regulatory definition of presence.

The p covariates that we considered included the linear effect of day of year, the quadratic effect of day of year, minimum daily temperature, mean daily noise, survey method (i.e., PAM or audio-visual), and the interaction between mean daily noise and survey method (Table 1). We collected the minimum daily temperature from multiple weather stations closest to the survey points, where the distance from the survey points and nearest weather station ranged from 6–31 km ($\bar{x}$ = 18.60, SD = 6.76). We included the quadratic effect of day of year because we hypothesized that detection probability would peak as the summer season progressed. Murrelets are active inland from April to September in Oregon and Washington, with a late-season peak in early- to mid-July (Jodice and Collopy 2000, Sanzenbacher et al. 2014, Pacific Seabird Group 2024). We included temperature because we predicted that temperature could affect calling activity, and included the minimum temperature, which correlates with the temperature at sunrise when murrelets are most active (Kuletz et al. 1994). Audio-visual surveys were not conducted during adverse weather conditions that might make seeing or hearing a murrelet more difficult. According to the audio-visual protocol we followed, the survey would need to be completed on another day under better conditions (Evans Mack et al. 2003). We were interested in evaluating whether noise would influence detection probability differently depending on the survey method, so we included the interactive effect between the 2. Here, we used the noise metric calculated from an ARU as a proxy for noise conditions during the completed audio-visual surveys. Survey method was also included as a covariate because we were interested in quantifying whether there was a difference in detection probability between PAM and audio-visual surveys. Although our study focused on murrelet detection probabilities, we included year and study area covariates on ψ to account for spatial and temporal heterogeneity in landscape use (Table 1). The study areas were delineated based on ownership. Because there is a large spatial distance between the Oregon points ($\bar{x}$ = 97 km, SD = 29 km, min–max = 60–135 km), we delineated by districts, Tillamook and West Oregon, to account for spatial variation. We standardized all continuous covariates to have a mean of 0 and standard deviation of 1. We then imputed missing data for 19 (0.5%) noise values with the standardized mean of 0. There were no indications that multicollinearity among covariates was an issue (i.e., all $|r| \leq 0.7$). We fit all plausible models to determine the most supported p and ψ models based on the Akaike information criterion corrected for small sample size (AIC_c; Anderson and Burnham 2002, Morin et al. 2020).

Following the approach of Gaylord et al. (2023), we used the most supported p model to estimate detection probability for all survey days for each survey method. We used the mvmeta R package (Gasparrini et al. 2012, Gasparrini and Armstrong 2013) and implemented a method-of-moments estimator for univariate random-effects meta-analysis (Jackson et al. 2013) to estimate an average daily detection probability (and its standard deviation) for each survey method across our surveys ($p_{daily.avg}$). For each survey method, we then used our estimate of $p_{daily.avg}$ to calculate a cumulative detection across a variable number of surveys $p_{c.d.p.} = 1 - (1 - p'_{daily})^n$, where $p_{c.d.p}$ is the cumulative detection probability, n is the number of surveys, and p'_{daily} is a value for daily detection probability that is sampled from our estimates of $p_{daily.avg}$. In particular, we simulated 10,000 iterations using a bootstrap simulation where we sampled p'_{daily} from a beta distribution after calculating shape parameters (α and β) using the mean and variance of $p_{daily.avg}$ for each survey method, where

$\alpha = \overline{p}_{daily.avg}\left(\frac{\overline{p}_{daily.avg}(1-\overline{p}_{daily.avg})}{\mathrm{var}(p_{daily.avg})}-1\right)$ and $\beta = (1-\overline{p}_{daily.avg})\left(\frac{\overline{p}_{daily.avg}(1-\overline{p}_{daily.avg})}{\mathrm{var}(p_{daily.avg})}-1\right)$. Thus, our estimates of $p_{c.d.p}$ incorporated our uncertainty in $p_{daily.avg}$.

Simulation evaluation

We also developed a simulation to evaluate the survey effort required, and the associated costs, to accurately determine murrelet use in a focal area at various spatial extents. We used cost estimates based on the actual and contracted costs that were incurred conducting surveys for this study and recognize that costs would fluctuate over time and differ across organizations, detection probabilities, and staff experience (Table 2). We examined costs for the first and second year of survey efforts to match the Marbled Murrelet Inland Survey Protocol, where the only change in cost was that ARUs are not purchased in year 2. We examined scenarios for project area sizes that ranged from 1 survey point to 10, and where the number of points being used by murrelets ranged from 1 to 10. For audio-visual surveys, we assumed points were surveyed in a random order, but that all points would be surveyed before a surveyor would return to a point to resurvey. For PAM surveys, we assumed ARUs were deployed simultaneously across all points. For a subset of simulations, we implemented a stopping rule for audio-visual surveys, where surveys may be terminated after murrelet presence is determined each year. We considered scenarios where each point was to be surveyed for 1, 2, 5, 10, and 20 survey days (unless the stopping rule applied). During simulations, we randomly sampled a daily detection probability (p'_{daily}) for each survey day for each survey method from our estimates of $p_{daily.avg}$ using the methods described above to incorporate our uncertainty in $p_{daily.avg}$ within these simulations. We ran each scenario for 10,000 iterations using program R (v4.4.0; R Core Team 2024). For each

TABLE 2 The estimated cost breakdown is shown per survey point associated with each survey method conducted for marbled murrelet (*Brachyramphus marmoratus*) in Washington and Oregon, USA, 2022–2023. All costs are in US dollars. Observer training and report writing are per season costs.

	Survey method	
Cost category	**Audio-visual**	**PAM**
Flagging point[1]	$23.30	NA
Point visit[2]	$560.00	$302.00
Observer training[3]	$1,500.00	NA
Equipment[4]	NA	$700.00
Validation and processing[5]	NA	$10.18
Report writing**	$19,256.05	$19,256.05

[1]Point setting (normally 1–7 per survey site).

[2]Point visit costs for both survey methods include salary, supply, field equipment, and infrastructure costs. For PAM surveys the cost includes the deployment and retrieval visit.

[3]Inland Marbled Murrelet observer training course, hotel, meal per diem, and fuel expenses. If field staff return for 3 years in a row, training is required every year for the first 2 years and a reduced cost training for the third year. New, untrained individuals must take the observer training each season.

[4]Initial costs associated with purchase of ARU: price of unit, SD card, and bungees.

[5]This cost includes processing data through PNW-Cnet, validation of tagged clips, validation ID training, and data storage costs.

**In our simulation, these rates were kept the same for both survey methods and are based on standard contracting rates. Report writing includes transcribing audio-visual survey results, downloading sound data, renaming files, quality assurance and quality control, data analysis, and final report.

iteration, we estimated the relative cost of completing the surveys as $\frac{Cost_{AV} - Cost_{PAM}}{Cost_{PAM}}$, where $Cost_{AV}$ was the total cost of the audio-visual surveys and $Cost_{PAM}$ was the total cost of the PAM surveys. Relative cost estimates >0 indicated that the audio-visual surveys cost more. The relative cost estimate can be interpreted as the percentage increase in cost, where a relative cost estimate of 0.8 indicates an 80% increase in cost to complete the surveys. Since the true objective is to accurately determine murrelet habitat use, we also summarized the proportion of simulations and the variability in this metric that correctly designated the area as having murrelets present.

RESULTS

We conducted 3,517 PAM survey days and 294 audio-visual survey visits across 88 points. The PNW-Cnet model produced 4,380 total marbled murrelet predictions, with the number of predictions per survey point ranging 0–507 ($\bar{x}$ = 49.77, SD = 93.98). We spent approximately 44 hours validating those predictions. There were 69 points with at least one murrelet detection across both survey methods, of those 69 detections, 28% were detected on the ARUs only and 6% were detected on audio-visual surveys only. Four ARUs did not detect murrelets during the survey season when at least one was detected during an audio-visual survey. In most instances, the ARU was recording during the audio-visual survey except on one occasion when the ARU had depleted batteries. The other instances where murrelets were detected on audio-visual surveys and not on the corresponding ARU recording do not mean that a murrelet was not calling. It only means that due to our confidence score threshold settings in PNW-Cnet, no murrelet keer calls met the ≥0.95 threshold to warrant further review based on our validation protocol. During the PAM surveys, we detected murrelets at 19 points that had no murrelets detected by any of the audio-visual surveys conducted at those same points.

Out of 70 models in our candidate set, 4 models were <2 ΔAIC_c (Table 3). Five models had a cumulative model weight >0.80. All other models had a model weight near 0 (Table A1). The most supported *p* model included quadratic effect of day of year, noise, survey method, and the interaction between survey method and noise (Table 4). We found that murrelet detection peaked in mid-July (Figure 2). As noise increased by approximately 6 dBFS at a survey point, the odds of detecting a murrelet decreased by 1.19 and 1.62 times for an audio-visual survey and a PAM survey, respectively (Figure 2). The odds of detecting murrelets on a given day were 2.70 times higher when implementing an audio-visual survey when compared to a PAM survey. The average daily detection probability across our surveys ($p_{daily.avg}$) for an audio-visual survey was 0.40 (SD = 0.17) and for a PAM survey it was 0.19 (SD = 0.10). The cumulative detection probability ($p_{c.d.p.}$) for PAM was 0.98 (95% CI = 0.96–1.00) after 19 survey days (Figure 2). For audio-visual surveys, the cumulative

TABLE 3 Table of top models ranked by Akaike's Information Criterion corrected for small sample size (AIC_c), change in AIC_c ($\Delta AICc$), model weights (w_i), and the number of parameters (k) for marbled murrelet (*Brachyramphus marmoratus*) in Washington and Oregon, USA, 2022–2023.

	Model	*k*	AIC	ΔAIC_c	w_i
1	ψ (Study area) *p* (Day of year + Day of year^2 + Noise × Survey method)	9	3118.43	0.00	0.29
2	ψ (Study area) *p* (Day of year + Day of year^2 + Noise × Survey method + Temperature)	10	3119.29	0.86	0.19
3	ψ (Study area) *p* (Day of year + Day of year^2 + Noise + Survey method)	8	3119.71	1.28	0.15
4	ψ (Study area + Year) *p* (Day of year + Day of year^2 + Noise × Survey method)	10	3120.38	1.95	0.11
5	ψ (Study area) *p* (Day of year + Day of year^2 + Noise + Survey method + Temperature)	9	3120.55	2.12	0.10

TABLE 4 Top model for marbled murrelet (*Brachyramphus marmoratus*) habitat use showing the mean, standard error (SE), and upper and lower 95% confidence intervals. Data were collected in Washington and Oregon, USA, 2022–2023.

Parameter	Mean	SE	Lower CI	Upper CI
Occupancy probability (ψ)				
Intercept	2.141	0.529	1.104	3.178
Study area: Tillamook district	−4.538	1.171	−6.833	−2.244
Study area: West Oregon district	−0.0003	0.748	−1.466	1.466
Detection Probability (p)				
Intercept	−1.177	0.066	−1.306	−1.047
Day of year	0.709	0.060	0.592	0.827
Day of year^2	−0.302	0.056	−0.411	−0.193
Noise	−0.480	0.068	−0.614	−0.347
Survey method: audio-visual	0.993	0.151	0.697	1.290
Noise × Survey method: audio-visual	0.306	0.163	−0.014	0.627

detection probability ($p_{c.d.p.}$) was 0.98 (95% CI = 0.96–1.00) after 9 visits (Figure 2). The most supported ψ model indicated there was a study area effect. Occupancy probability was estimated at 0.89 (95% CI = 0.75–0.96) at Jim Creek, 0.89 (95% CI = 0.75–0.96) in the West Oregon district, and 0.08 (95% CI = 0.01–0.41) in the Tillamook district.

Without a stopping rule, we found audio-visual surveys cost substantially more to complete as the number of points and surveys per point increased, especially in year 2 of the monitoring effort (Figure 3). In year 1, audio-visual surveys were less expensive or the same cost as PAM when conducting one visit when 4 or more points were surveyed (min–max = −0.10– − 0.01) but were around 1–5% more than PAM when 3 or fewer points were surveyed (min–max = 0.01–0.05). When conducting 2 visits per site in year 1, audio-visual surveys cost 8–9% more than PAM (min–max = 0.08–0.09), likely due to costs associated with each audio-visual visit. As the number of visits and number of points increased from 5–20 visits in year 1 and in all instances in year 2, the relative cost increased for audio-visual surveys (min–max = 0.16–5.12; Figure 3A).

When including a stopping rule where surveys end when presence is established, audio-visual surveys were generally more costly in year 2, with some exceptions. In year 2, the cost of audio-visual surveys equalled PAM surveys at 1–5 visits when murrelets were using 10 points. In year 1 when conducting 1–20 visits, audio-visual surveys cost less than or equal to PAM surveys when surveying at least 3 points (min–max = −0.24–0.00) and when murrelets were using more points in each subsequent number of site visits (Figure 3B).

In our simulation, we found the most consistent correct determinations of murrelet presence (i.e., proportion of correct detections at 1.0 and coefficient of variation near 0) occurred when points were surveyed 20 times each, but there was some nuance in these estimates (Figure 4). Indeed, the variability in accurately determining murrelet presence was substantial for both audio-visual (min–max = 13.03–125.15) and PAM (min–max = 38.02–209.07) surveys when conducting one survey visit if murrelets were using approximately 1–8 points for audio-visual surveys and 1–10 points for PAM (Figure 4). When conducting 2, 5, and 10 audio-visual survey visits we found consistent determinations of presence if murrelets were using at least 4, 2, and 1 point, respectively. When conducting 2, 5, and 10 PAM survey visits we found consistent determinations of presence if murrelets were using at least 10, 4, and 2 points, respectively (Figure 4).

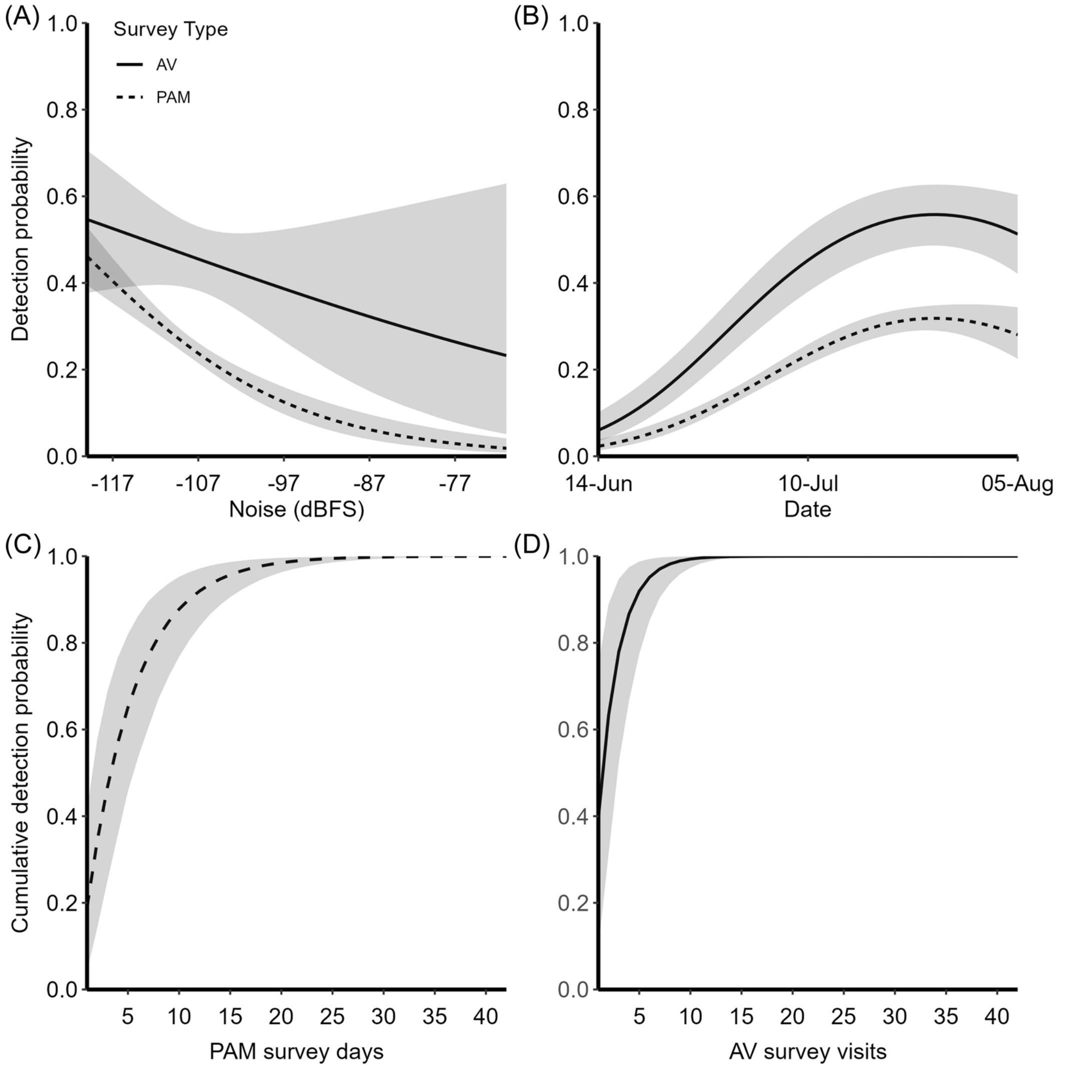

FIGURE 2 Marbled murrelet (*Brachyramphus marmoratus*) detection probability with variable noise (A) and across days of the year (B), and cumulative detection probability ($p_{c.d.p}$) by survey method (C, D) across a variable number of survey days. Shaded area represents 95% confidence interval (CI). Data were collected in Washington and Oregon, USA, 2022–2023.

DISCUSSION

Cost-effective survey methods are needed for rare and cryptic wildlife for managers to meet information requirements within real-world budgetary and time constraints. Here, we conducted a study to compare 2 survey methods, PAM and audio-visual surveys, for the detection of murrelets in forest habitats and estimated the relative cost of each survey method across different levels of effort. Like Borker et al. (2015), we found PAM had reduced detection probabilities on a single survey day, but the number of survey days quickly increased for PAM at little-to-no extra costs to the point where cumulative detection probability using PAM quickly exceeded audio-visual surveys. Thus, our findings suggest that PAM is an efficient, cost-effective alternative to determine the presence of murrelets.

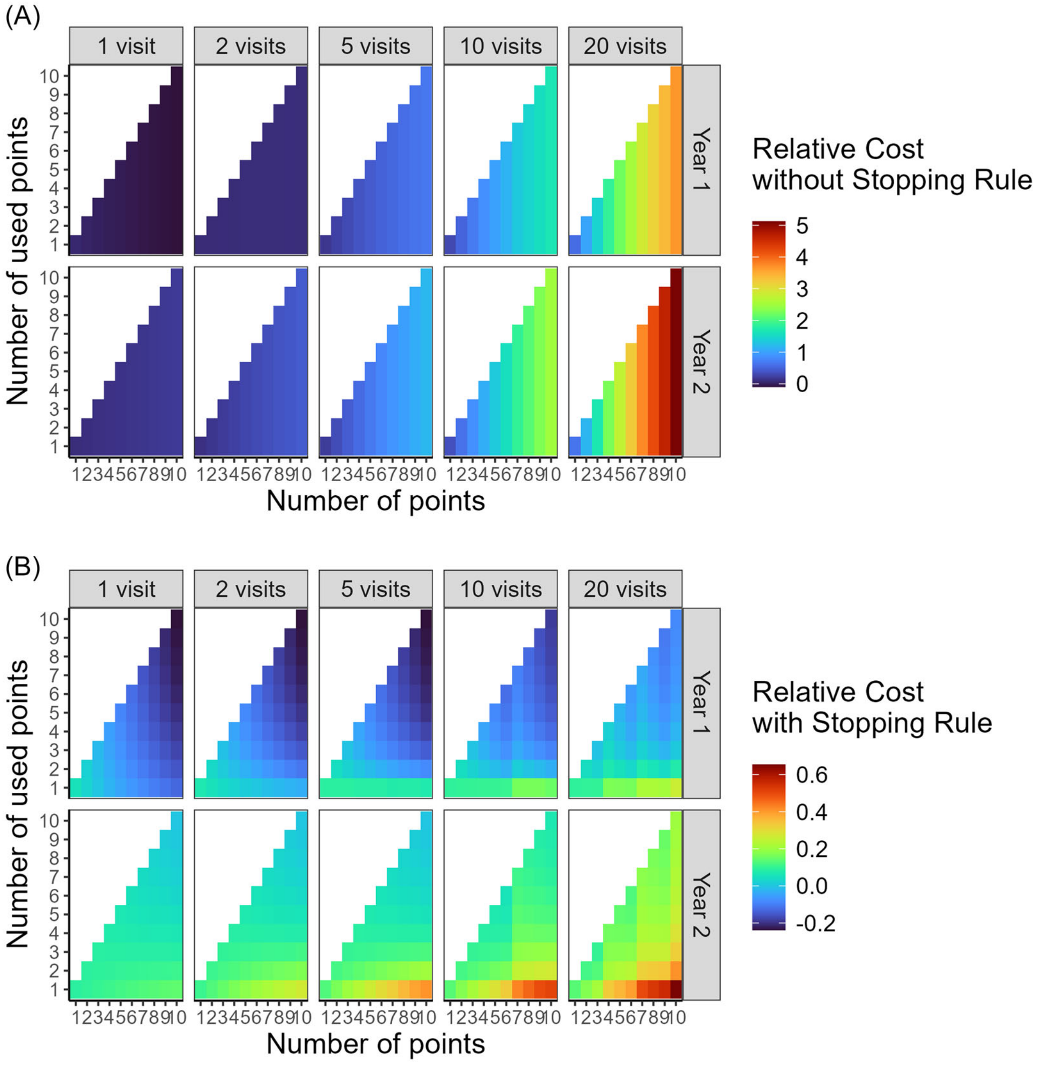

FIGURE 3 Simulation results of relative costs of audio-visual surveys when compared to PAM for marbled murrelet (*Brachyramphus marmoratus*). The top panels (A) show the relative cost without a stopping rule, and the bottom panels (B) show the relative cost with a stopping rule. Within each panel, the figures present relative costs in year 1 (top) and year 2 (bottom). The red and orange colors represent greater relative cost.

Although the per survey day detection probability was higher for audio-visual surveys, the cumulative detection probability across surveys is used to infer absence given that no detections occurred. Nine audio-visual surveys were needed at each survey point to reach a high cumulative detection probability for murrelets, which requires a technician to visit a point in the early morning hours on 9 separate days. Due to budgetary and logistical constraints, audio-visual surveys are often only conducted at a point on 1–2 mornings within a breeding season. Passive acoustic monitoring using ARUs were able to detect murrelets if present with high confidence after 19 survey days. Therefore, the same level of confidence can be achieved when using PAM surveys, which would require a technician for only 2 short site visits—once to deploy and once to retrieve the ARU. We were able to deploy ARUs for an average of 40 days with little issue with data storage needs or battery life. Thus, PAM surveys resulted in higher confidence determinations of murrelet presence without requiring additional field efforts.

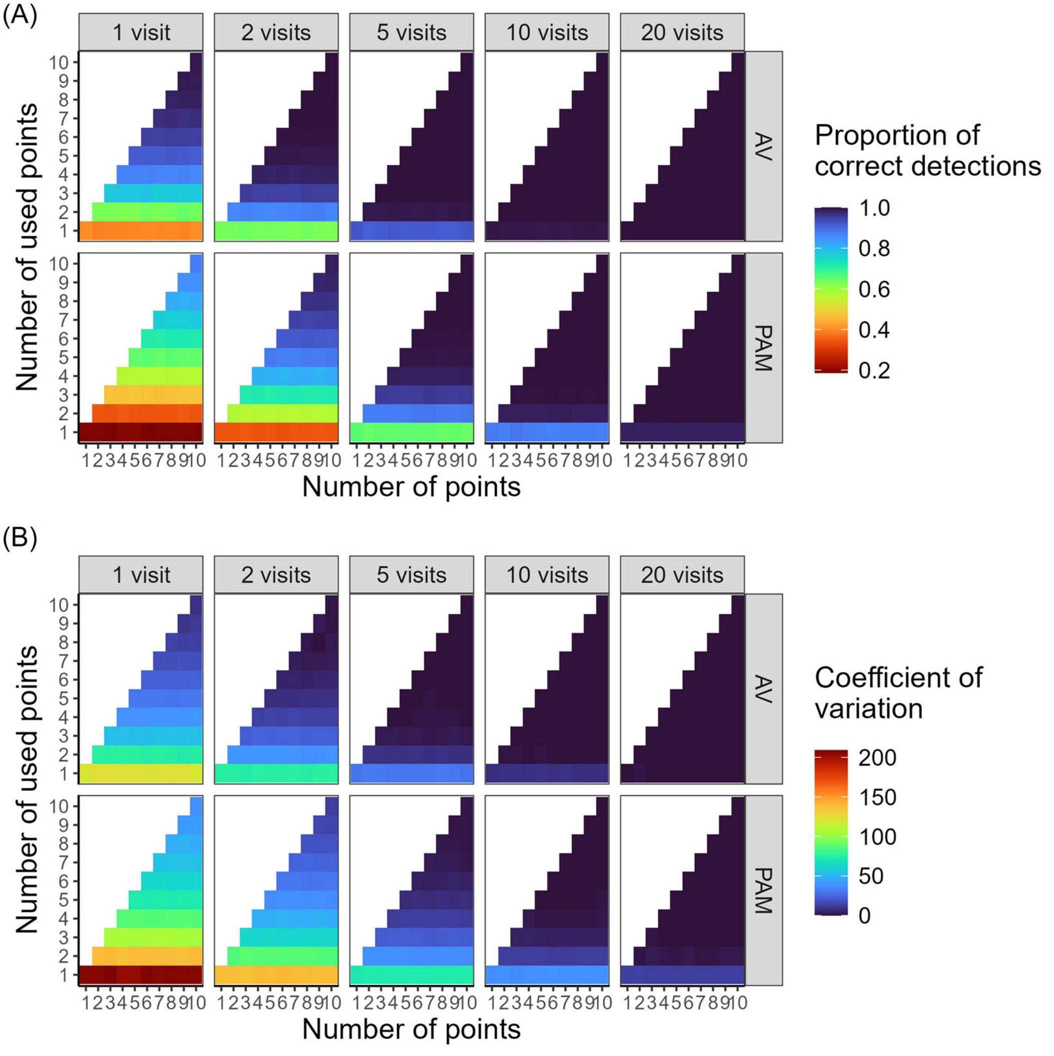

FIGURE 4 Simulation results of correctly defining a point as having marbled murrelet (*Brachyramphus marmoratus*) presence. The top panels (A) show the proportion of simulations that correctly determined presence. The bottom panels (B) show the variability (based on coefficient of variation) in achieving the correct determination of presence. Within each panel, the figures present the survey method audio-visual (AV; top) and PAM (bottom).

Given that most murrelet survey efforts occur across multiple survey points, we developed a simulation model to evaluate our ability to make accurate determinations of murrelet presence across different project area sizes (represented by the different number of survey points in our simulations). Importantly, by allocating surveys across spatial and temporal replicates the surveys must overcome an additional source of uncertainty: murrelet use of the area under study. Our results demonstrated that the number of surveys needed to correctly identify murrelet presence increased as the proportion of points used by murrelets decreased. Importantly, the increase in survey effort resulted in substantially increased costs for audio-visual surveys with no realized increase in costs for PAM surveys because ARUs are deployed at all survey points to record across the entire survey season regardless of proportion of area used by murrelets. Moreover, the number of points used by murrelets is never known *a priori*.

Thus, murrelet survey protocols do not have the ability to scale survey effort based on the proportion of points being used by murrelets.

There are aspects of our study that should be noted with respect to detection probability estimates. We focused our surveys during a time presumed to have peak murrelet inland activity. If our surveys began earlier in the year when murrelets make fewer inland flights, overall detections would be lower and therefore would require more survey occasions to reach a high cumulative detection probability (Peery et al. 2004). Indeed, our results concerning detection probability are tied to points where murrelets were present during our survey period. Similarly, our simulations sampled daily detection probabilities from across our survey period, and our figures depict results that were summarized across 10,000 iterations. Our aim was to propagate the uncertainty in the daily detection probability estimates and the uncertainty associated with the timing of surveys. Our simulation approach was helpful for observing trends and developing generalizable guidelines based on empirical data. However, surveys conducted in the field for specific monitoring efforts will likely have more nuance. For example, we found support for a quadratic effect of day of year, which indicates that cumulative detection probability would be lower than the mean value we report herein if surveys were only conducted outside the window with the peak daily detection probabilities. Our finding of variable detection probabilities across the season highlights the importance of choosing the time of year when surveys are conducted. Although our simulations incorporated this process and variability, maximizing detection probabilities is critical regardless of the survey method used.

Our per-survey detection probability when using PAM is likely biased low due to our human validation process. Specifically, we only reviewed audio clips that met our ≥0.95 confidence score threshold, so we likely missed some keer calls in our audio data. Reviewing every audio clip predicted to contain murrelet vocalizations would be cost prohibitive based on technician time, given the tradeoffs between precision and recall as a function of confidence score threshold (Duarte et al. 2024). A lower confidence score threshold would require substantial efforts to remove false-positive detections from the data. Using our protocol and PNW-Cnet (Ruff et al. 2023), we were able to efficiently validate murrelet vocalizations to the point that there is relatively little drawback to deploying ARUs for longer periods of time. In fact, as the number of days an ARU is deployed increases there is a reduction in per survey cost. Our results demonstrated that long ARU deployments miss some murrelet vocalizations when using a relatively high confidence score threshold to determine murrelet presence.

In general, we found that the cost estimates between the survey methods were more similar with a small number of surveys, particularly when using a stopping rule. However, as the number of surveys increased, audio-visual survey costs substantially increased due to technician time in the field. On the other hand, the cost of PAM surveys was invariant to the number of survey days and only increased as the number of points to be surveyed increased. The additional cost was associated with purchasing the ARUs and associated equipment, and these additional costs were not a factor in the second year of surveys. There are 2 additional sources of cost that we did not consider in our simulation. The first is field crew safety. The audio-visual surveys regularly require technicians to drive on remote forest roads and hike in dense and steep forests at night or to backpack out to survey points to camp alone the night before the survey. For PAM surveys, technicians can deploy or retrieve multiple ARUs each day during daylight hours. Although safety is always a concern with any fieldwork, we observed fewer safety incidents when fieldwork occurred during daylight hours. The second is the cost associated with developing a CNN and workflow to process and validate large volumes of acoustic data. The cost of developing an accurate CNN can be quite high, given the expertise and technician time required to amass high-quality training data and develop the classifier. We opted to omit this cost in our assessment because PNW-Cnet (Ruff et al. 2023) and other open source CNNs, such as Perch (Ghani et al. 2023) and BirdNet (Kahl et al. 2021), have already been developed and can accurately classify a variety of species across various regions of the world. Thus, most of the cost associated with developing a useful CNN to help facilitate PAM have already been realized for avian communities generally and murrelets specifically.

Although the 2003 Marbled Murrelet Inland Survey Protocol did not consider auditory detections sufficient evidence of occupancy (Evans Mack et al. 2003), the recently revised protocol recognizes auditory detections as valid for occupancy determinations when multiple detections are made (Pacific Seabird Group 2024). As such, integrating PAM into regulatory frameworks as an alternative or complement to traditional audio-visual surveys may be useful. Our findings indicate that PAM can meet or exceed the detection confidence thresholds outlined in the new protocol, with significantly fewer site visits and lower overall cost. In addition, PAM produces verifiable digital records that can be archived, sent for expert review, reanalyzed with future classifier improvements, and used to track call density patterns that may ultimately inform nesting status or habitat quality (Duarte et al. 2024). While further research is needed to refine thresholds linking vocal activity to nesting behavior, our results suggested that PAM coupled with PNW-Cnet offers a rigorous, transparent, and scalable solution for murrelet monitoring under the revised regulatory standards.

MANAGEMENT IMPLICATIONS

Managers can use the information we present herein to make informed decisions concerning the use of audio-visual surveys, PAM surveys, or both, depending on the needs of the project. While PAM does not lead to the detection of murrelet occupied behaviors, our study provides quantitative evidence that PAM is an effective alternative to determine murrelet presence that provides cost savings when done across multiple survey points and years. Given that the newest murrelet survey protocol allows for a presence approach to classify project areas as occupied, it seems PAM and audio-visual surveys represent acceptable methods to fulfill regulatory monitoring requirements for this threatened species.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

Our study adhered to all relevant guidelines and protocols for access to our study areas. No animals were handled during this study. All surveys involved passive observations.

DATA AVAILABILITY STATEMENT

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APPENDIX

(See Table A1).

TABLE A1 All models ranked by Akaike's Information Criterion corrected for small sample size (AIC_c), change in AIC_c ($\Delta AICc$), model weights (w_i), and the number of parameters (k) for marbled murrelet (*Brachyramphus marmoratus*) in Washington and Oregon, USA, 2022–2023.

	Model	*k*	AIC	ΔAIC_c	w_i
1	ψ (Study area) *p* (Day of year + Day of year^2 + Noise × Survey method)	9	3118.43	0.00	0.29
2	ψ (Study area) *p* (Day of year + Day of year^2 + Noise × Survey method + Temperature)	10	3119.29	0.86	0.19
3	ψ (Study area) *p* (Day of year + Day of year^2 + Noise + Survey method)	8	3119.71	1.28	0.15
4	ψ (Study area + Year) *p* (Day of year + Day of year^2 + Noise × Survey method)	10	3120.38	1.95	0.11
5	ψ (Study area) *p* (Day of year + Day of year^2 + Noise + Survey method + Temperature)	9	3120.55	2.12	0.10
6	ψ (Study area + Year) *p* (Day of year + Day of year^2 + Noise × Survey method + Temperature)	11	3121.25	2.82	0.07
7	ψ (Study area + Year) *p* (Day of year + Day of year^2 + Noise + Survey method)	9	3121.66	3.23	0.06
8	ψ (Study area + Year) *p* (Day of year + Day of year^2 + Noise + Survey method + Temperature)	10	3122.50	4.07	0.04
9	ψ (Study area) *p* (Day of year + Noise × Survey method)	8	3148.19	29.76	0.00
10	ψ (Study area) *p* (Day of year + Noise + Survey method)	7	3149.86	31.43	0.00
11	ψ (Study area) *p* (Day of year + Noise × Survey method + Temperature)	9	3150.13	31.70	0.00
12	ψ (Year) *p* (Day of year + Day of year^2 + Noise × Survey method)	8	3150.14	31.71	0.00
13	ψ (Study area + Year) *p* (Day of year + Noise × Survey method)	9	3150.15	31.72	0.00
14	ψ (Year) *p* (Day of year + Day of year^2 + Noise × Survey method + Temperature)	9	3151.00	32.58	0.00
15	ψ (Year) *p* (Day of year + Day of year^2 + Noise + Survey method)	7	3151.42	32.99	0.00
16	ψ (Study area) *p* (Day of year + Noise + Survey method + Temperature)	8	3151.80	33.37	0.00
17	ψ (Study area + Year) *p* (Day of year + Noise + Survey method)	8	3151.82	33.39	0.00
18	ψ (Study area + Year) *p* (Day of year + Noise × Survey method + Temperature)	10	3152.08	33.65	0.00
19	ψ (Year) *p* (Day of year + Day of year^2 + Noise + Survey method + Temperature)	8	3152.26	33.83	0.00
20	ψ (Study area + Year) *p* (Day of year + Noise + Survey method + Temperature)	9	3153.75	35.32	0.00
21	ψ (Study area) *p* (Day of year + Day of year^2 + Noise)	7	3156.87	38.44	0.00
22	ψ (Study area + Year) *p* (Day of year + Day of year^2 + Noise)	8	3158.82	40.39	0.00
23	ψ (Study area) *p* (Day of year + Day of year^2 + Survey method)	7	3178.87	60.44	0.00
24	ψ (Year) *p* (Day of year + Noise × Survey method)	7	3179.90	61.47	0.00
25	ψ (Study area + Year) *p* (Day of year + Day of year^2 + Survey method)	8	3180.83	62.40	0.00
26	ψ (Year) *p* (Day of year + Noise + Survey method)	6	3181.57	63.14	0.00
27	ψ (Year) *p* (Day of year + Noise × Survey method + Temperature)	8	3181.84	63.41	0.00

(Continues)

TABLE A1 (Continued)

	Model	k	AIC	ΔAIC_c	w_i
28	ψ (Study area) p (Day of year + Noise)	6	3182.12	63.69	0.00
29	ψ (Year) p (Day of year + Noise + Survey method + Temperature)	7	3183.50	65.07	0.00
30	ψ (Study area + Year) p (Day of year + Noise)	7	3184.07	65.64	0.00
31	ψ (Year) p (Day of year + Day of year^2 + Noise)	6	3188.58	70.15	0.00
32	ψ (Study area) p (Day of year + Day of year^2)	6	3210.16	91.73	0.00
33	ψ (Year) p (Day of year + Day of year^2 + Survey method)	6	3210.58	92.15	0.00
34	ψ (Study area) p (Day of year + Day of year^2 + Temperature)	7	3210.77	92.34	0.00
35	ψ (Study area + Year) p (Day of year + Day of year^2)	7	3212.12	93.69	0.00
36	ψ (Study area + Year) p (Day of year + Day of year^2 + Temperature)	8	3212.72	94.29	0.00
37	ψ (Year) p (Day of year + Noise)	5	3213.82	95.39	0.00
38	ψ (Study area) p (Day of year + Survey method)	6	3217.46	99.03	0.00
39	ψ (Study area + Year) p (Day of year + Survey method)	7	3219.41	100.98	0.00
40	ψ (Year) p (Day of year + Day of year^2)	5	3241.87	123.44	0.00
41	ψ (Year) p (Day of year + Day of year^2 + Temperature)	6	3242.48	124.05	0.00
42	ψ (Study area) p (Day of year)	5	3243.47	125.04	0.00
43	ψ (Study area) p (Day of year + Temperature)	6	3245.32	126.89	0.00
44	ψ (Study area + Year) p (Day of year)	6	3245.42	127.00	0.00
45	ψ (Study area+ Year) p (Day of year + Temperature)	7	3247.27	128.84	0.00
46	ψ (Year) p (Day of year + Survey method)	5	3249.17	130.74	0.00
47	ψ (Year) p (Day of year)	4	3275.18	156.75	0.00
48	ψ (Year) p (Day of year + Temperature)	5	3277.03	158.60	0.00
49	ψ (Study area) p (Noise × Survey method)	7	3290.39	171.96	0.00
50	ψ (Study area + Year) p (Noise × Survey method)	8	3292.34	173.91	0.00
51	ψ (Study area) p (Noise + Survey method)	6	3293.72	175.29	0.00
52	ψ (Study area + Year) p (Noise + Survey method)	7	3295.68	177.25	0.00
53	ψ (Year) p (Noise × Survey method)	6	3322.10	203.67	0.00
54	ψ (Study area) p (Noise + Temperature)	6	3322.87	204.44	0.00
55	ψ (Study area + Year) p (Noise + Temperature)	7	3324.83	206.40	0.00
56	ψ (Year) p (Noise + Survey method)	5	3325.44	207.01	0.00
57	ψ (Study area) p (Noise)	5	3337.16	218.73	0.00
58	ψ (Study area + Year) p (Noise)	6	3339.12	220.69	0.00
59	ψ (Year) p (Noise + Temperature)	5	3354.60	236.17	0.00
60	ψ (Year) p (Noise)	4	3368.87	250.44	0.00
61	ψ (Study area) p (Survey method + Temperature)	6	3410.95	292.52	0.00
62	ψ (Study area + Year) p (Survey method + Temperature)	7	3412.90	294.48	0.00

TABLE A1 (Continued)

	Model	*k*	AIC	ΔAIC_c	w_i
63	*ψ* (Study area) *p* (Survey method)	5	3430.20	311.77	0.00
64	*ψ* (Study area + Year) *p* (Survey method)	6	3432.15	313.73	0.00
65	*ψ* (Year) *p* (Survey method + Temperature)	5	3442.65	324.22	0.00
66	*ψ* (Study area) *p* (Temperature)	5	3446.29	327.86	0.00
67	*ψ* (Study area + Year) *p* (Temperature)	6	3448.24	329.81	0.00
68	*ψ* (Year) *p* (Survey method)	4	3461.89	343.46	0.00
69	*ψ* (Year) *p* (Temperature)	4	3477.97	359.54	0.00
70	*ψ* (.) *p* (.)	2	3497.01	378.58	0.00