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Tools and Technology

A Comparison of Automated and Traditional Monitoring Techniques for Marbled Murrelets Using Passive Acoustic Sensors

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ABSTRACT Autonomous sensors and automated analysis have great potential to reduce cost and increase efficacy of wildlife monitoring. By increasing sampling effort, autonomous sensors are powerful at detecting rare and elusive species such as the marbled murrelet (*Brachyramphus marmoratus*). New approaches must be tested for comparability to existing methodologies, so we compared the results of inland audio–visual and of automated acoustic monitoring for marbled murrelets, conducted during the 2010 breeding season, at 7 sites in the Santa Cruz Mountains, California, USA. We found automated acoustic surveys and analysis had fewer detections per morning compared with audio–visual surveyors, but the rate of automated acoustic detections per morning was positively and strongly correlated with the rate of audio–visual detections per mornings ($r = 0.96$, $P < 0.01$). Furthermore, acoustic monitoring sampled 10 times more mornings per site ($\bar{x} = 48$) than were monitored by human surveyors ($\bar{x} = 4.4$) at a comparable cost. We used resampling to estimate the power to detect murrelet presence with acoustic sensors at >80% within 8 continuous days of recordings, even at low-activity sites. Our results suggest that autonomous sensor and automated analysis approaches could greatly increase the scale and efficacy of murrelet monitoring, allowing for more cost-effective surveying of large and remote areas of potential habitat, as well as, improved ability to measure changes in inland activity. Further study of passive acoustic recordings would be valuable to examine for acoustic signs of breeding phenology, and site occupancy, if acoustic surveys are to replace the utility of audio–visual surveys.

KEY WORDS bioacoustics, *Brachyramphus marmoratus*, California, management, marbled murrelet, methods, monitoring, murrelets, wildlife.

Marbled murrelets (*Brachyramphus marmoratus*), a small seabird (188–269 g) that nests in old-growth forest from central California to coastal Alaska, USA, are recognized as exceptionally difficult to monitor because of low detection rates and remote habitats (Nelson 1997). In fact, the first record of a marbled murrelet nest was not discovered until 1974, making it one of the last bird species in North America to have its nest site described (Binford et al. 1975). They are sensitive to habitat disturbance (Malt and Lank 2009), and have been U.S. Federally listed in California, Oregon, and Washington as "threatened" since 1992 (Department of Interior Fish and Wildlife Service 1992). In particular, their requirement for old-growth forest for breeding has led to significant conservation conflict with commercial timber harvest interests (Raphael 2006). Management decisions are currently based on a combination of coastal surveys, watershed-scale radar surveys and inland audio–visual surveys. Audio–visual surveys by human observers measure site occupancy, presence or probable absence, and map breeding distribution (Mack et al. 2003).

However, human surveys are logistically challenging and costly. Recent comparisons of monitoring data from radar surveys and audio–visual surveys have revealed potential sources of detection error, including observer skill (Bigger et al. 2006*b*) and murrelet visibility (Rodway and Regehr 2000). Despite advances in radar monitoring (Bigger et al. 2006*a*), radar units are limited to forest stands with road access and sites with open lines of sight (Mack et al. 2003). Although radar may be an effective tool for watershed-wide population estimates in accessible areas (Burger 2001, Cooper and Blaha 2002), it has not been considered a

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substitute for the inland audio–visual surveys (Mack et al. 2003), which can be used to determine critical breeding habitat.

Here, we test the use of autonomous passive acoustic sensors and automated acoustic analysis as an alternative to traditional inland monitoring techniques. Autonomous acoustic sensors are increasingly applied as a tool for monitoring elusive wildlife, and automated acoustic analysis helps process large data streams to provide information at large spatial and temporal scales (Van Parijs et al. 2009, Buxton 2010, Thompson et al. 2010). Autonomous acoustic sensors are a potentially cost-effective way to assess presence and relative activity levels across large spatial scales for marbled murrelets. In addition, they can help reduce high sampling variability, observer bias, and costly repetitive visits to remote field sites common in traditional surveys.

We explored correlations between murrelet activity measured using traditional inland audio–visual surveys with indices measured using autonomous acoustic sensor data processed using automated acoustic analysis at 7 murrelet monitoring sites in the Santa Cruz Mountains, California. In particular, we examined the power of autonomous acoustic monitoring and automated analysis (hereafter, referred to as "acoustic monitoring") to detect murrelets and measure levels in activity, as compared with human audio–visual surveys.

STUDY AREA AND SPECIES

We selected 7 historical inland murrelet monitoring sites in Big Basin and Butano State Parks, Santa Cruz County, California (D. L. Suddjian, Command Oil Spill Trustee Council, unpublished data; Supporting Material, Fig. S1 and Table S1). Sites were selected to encompass a range of murrelet activity levels based on data from historical counts in the Santa Cruz Mountains. This population, in Zone 6 of the Northwest Forest Plan, is the southernmost extent of the marbled murrelet range (Raphael 2006). Murrelet detection rates during traditional surveys in Big Basin State Park have declined 92% from 1995 to 2008, from a mean of 54.5 morning detections/site to 4 morning detections/site (D. L. Suddjian, Command Oil Spill Trustee Council, unpublished data).

METHODS

California State Parks and a private contractor conducted 31 standard inland audio–visual surveys at 7 sites between 16 June and 5 August 2010. Surveys by 5 trained observers were conducted according to inland forest survey protocol (IFSP; Mack et al. 2003), for 150 min beginning 30 min before dawn. All surveys were conducted within the IFSP monitoring window of 15 April–5 August.

At each of the 7 monitoring sites, we also deployed a SongMeter SM2 passive acoustic recorder (Wildlife Acoustics, Concord, MA). We secured each SongMeter to the trunk of a tree 3–4 m off the ground within 10 m of the human surveyor's location. We deployed sensors in mid-June and collected them in September; we programmed sensors to record for 3 hours, beginning an hour before dawn. For this study, we only analyzed recordings during the IFSP survey period from 15 June to 5 August. We attached an omni-directional microphone (SMX-II; sensitivity: $\bar{x} = -36 \pm 4$ dB, frequency response: 20 Hz–20 kHz, signal-to-noise ratio: >62 dB) directly to the SongMeter, and recorded on a single channel at a sampling rate of 20 kHz. This sample rate captured the range of marbled murrelet vocalization as well as other birds present in the study area.

To detect marbled murrelet "keer" calls (Nelson 1997), we identified sounds of interest using the spectrogram cross-correlation detection tool in the eXtensible BioAcoustic Tool (XBAT; Figueroa 2007)—a bioacoustics analysis package for MATLAB (The MathWorks 2010). We modified the software to improve performance in this complicated soundscape. Specifically, we added 1) stationary noise reduction to remove the noise component that is uniformly distributed across time; 2) frequency shifting to increase detection robustness to shifts in absolute frequency; and 3) an approach that uses the distribution of cross-correlation scores across templates for more fine-grained detection accuracy. For search templates, we selected 5 murrelet keer calls of high signal-to-noise ratio from the field recordings collected for this study. We carried out processing with spectrograms calculated at a fast Fourier transform size of 512, Hann window, and frame advance setting of 0.336.

After automated processing, we manually reviewed all events identified as potential murrelet calls by the detector. Thus, a human reviewer confirmed all murrelet vocalizations and removed all events that were incorrectly classified by the software by viewing the spectrogram and listening to the recording. Most misclassifications were generated by the songs of American robins (*Turdus migratorius*) and songs of Swainson's thrush (*Catharus ustulatus*), with features similar to murrelet keer calls. Finally, we grouped all murrelet calls separated by <5 s into calling bouts to meet IFSP guidelines (Mack et al. 2003); each calling bout is henceforth referred to as a murrelet detection.

We compared human surveys and automated acoustic monitoring at 2 temporal scales. At the seasonal scale, we calculated mean rate of morning detections for all sites ($n = 7$) with each method (inland audio–visual and acoustic) and compared them using Pearson's product-moment correlation coefficient. We calculated a 95% confidence interval around the correlation coefficient by resampling 7 points with replacement bootstrapped 1,000 times to examine the influence of outliers. At the individual morning scale, we compared automated and human IFSP detections during simultaneous surveys ($n = 29$) using the same approach (Supporting Material, Fig. S2). Two sample comparisons of detection rates were done with paired Wilcoxon signed-ranked tests to address non-normality. All statistical comparisons and analysis were conducted in the R programming environment (R Development Core Team 2011). We used a P-value threshold of 0.05 to assess significance and a P-value of 0.10 for trends (i.e., marginal support) for all tests.

We used a resampling exercise to estimate the power of acoustic monitoring to detect the presence of murrelets if not deploying sensors for the entire breeding season. We calculated the cumulative likelihood of detecting ≥1 murrelet call given successive mornings of acoustic monitoring from resampled continuous sets of mornings with random start dates during the IFSP monitoring window.

We estimated costs of a hypothetical 10-year acoustic monitoring program based on initial equipment investment and annual staff time needed to collect and analyze recordings, and produce a final summary report (Supporting Material, Table S2). We compared our estimates of cost per site per season with the cost of previous marbled murrelet monitoring activities conducted at Big Basin State Park (P. Halbert, personal communication).

RESULTS

Between 15 June and 5 August, autonomous acoustic sensors recorded for 338 mornings at 7 sites, tallying 2,463 murrelet detections. Simultaneously, we conducted 29 inland audio–visual surveys, with a minimum of 3 surveys/site, and tallied 724 detections. Both acoustic monitoring and audio–visual surveys detected marbled murrelets at all 7 monitoring sites (Table 1; Fig. 1).

Automated Recording and Analysis

Autonomous sensors performed well, with only one sensor malfunctioning after 34 mornings. Other sensors recorded from 45 to 52 continuous mornings spanning peak murrelet activity. These sensors functioned for as long as 82 mornings, but we removed these recordings outside the IFSP window from our analysis. Spectrogram cross-correlation flagged 19,216 sounds as potential murrelet vocalizations all of which were reviewed by 2 human observers (34 hr of review). Thirty-eight percent of those sounds were positively identified as murrelets (7,218 calls). Of those, 2,463 murrelet calls occurred >5 s after other murrelet calls and were recorded as independent murrelet detections.

Seasonal Comparisons of Acoustic Activity and Human Audio–Visual Surveys

At all monitoring sites the mean rate of automated acoustic detections was less than half of the mean rate of human inland audio–visual detections ($\bar{x} = 6.8$ vs. 19.3 detections/morning; 1-tailed paired Wilcoxon signed-rank test, $W = 2$, $P = 0.02$; Table 1). Because, on average, autonomous acoustic sensors sampled 10 times more mornings than human surveyors, the mean total number of automated acoustic detections across sites throughout the season was >3 times higher than the total number of human detections per site; however, nonparametric approaches found only marginal support for a greater central tendency ($\bar{x} = 351.9$ vs. 103.4 detections/season, 1-tailed paired Wilcoxon signed-rank test, $W = 23.5$, $P = 0.06$). The mean rate (acoustic detections per morning) of acoustic activity at each site was positively correlated with the mean rate of human audio–visual detections per morning (Bootstrapped Pearson's correlation coeff. = 0.96, 95% CI = 0.857–0.999; Fig. 2).

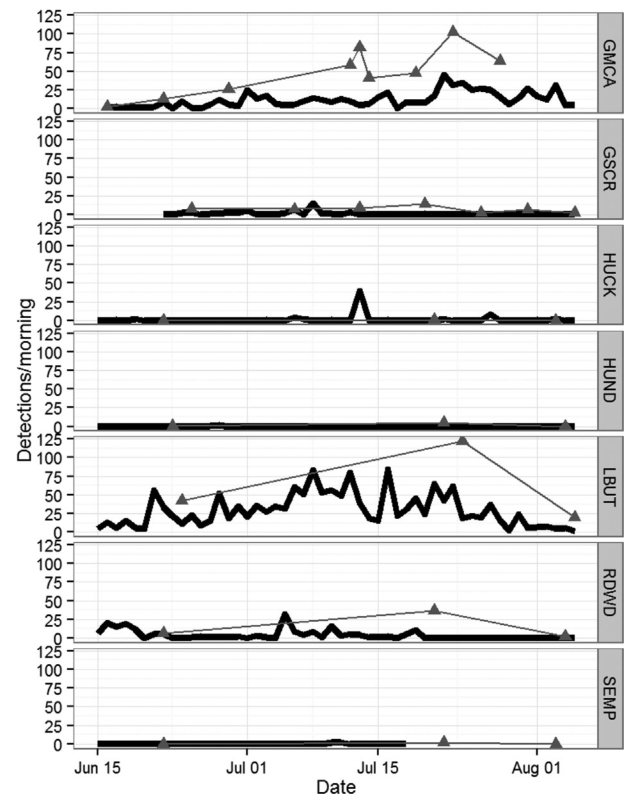

Figure 1. Seasonal activity of marbled murrelets detected by automated acoustic sensors and analysis (black lines) and human audio–visual surveys (gray triangles connected by lines) during the 2010 breeding season at 7 sites in the Santa Cruz Mountains, California, USA. GMCA, Gazos Camp; GSCR, Girl Scout Creek; HUCK, Huckleberry; HUND, 100 Acre Woods; LBUT, Little Butano Creek; RDWD, Redwood Meadow; SEMP, Sempevirens.

Table 1. Marbled murrelet activity detected during the 2010 breeding season by acoustic and traditional audio–visual surveys at 7 sites in the Santa Cruz Mountains, California, USA.

	Automated acoustic detections/morning			Human detections/morning		
Site	$\bar{x}$	SD	Mornings sampled	$\bar{x}$	SD	Mornings sampled
GMCA	11.9	10.5	51	48.6	32.4	9
GSCR	1.0	2.5	45	6.9	4.2	7
HUCK	1.3	5.6	52	0.3	0.6	3
HUND	0.1	0.3	52	2.0	2.6	3
LBUT	29.4	22.1	52	61.3	53.7	3
RDWD	3.9	6.6	52	15.3	18.9	3
SEMP	0.1	0.5	34	0.7	1.2	3

GMCA, Gazos Camp; GSCR, Girl Scout Creek; HUCK, Huckleberry; HUND, 100 Acre Woods; LBUT, Little Butano Creek; RDWD, Redwood Meadow; SEMP, Sempevirens.

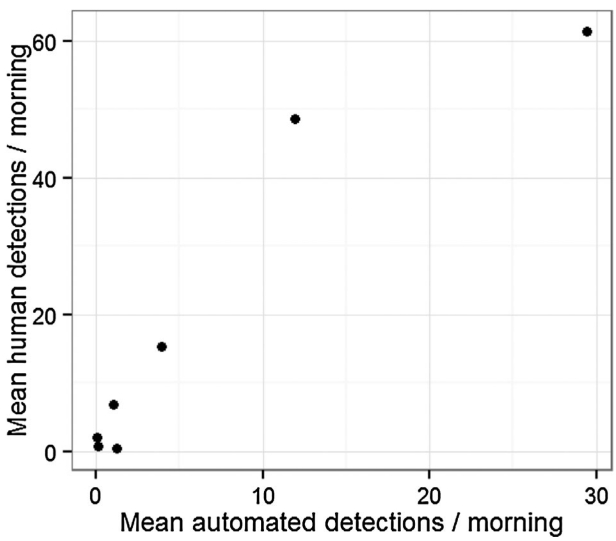

Figure 2. The relationship between relative activity levels of marbled murrelets measured with 2 methods, automated acoustic monitoring, and human audio–visual surveys during the 2010 breeding season, at 7 sites the Santa Cruz Mountains, California, USA.

Simultaneous Comparisons of Acoustic Activity and Human Audio–Visual Surveys

Automated sensors had fewer detections than inland audio–visual surveyors ($\bar{x} = 4.8$ vs. 24.9 detections/morning [1-tailed paired Wilcoxon signed-rank test, $W = 9$, $P < 0.01$]), but these indices of activity were positively correlated (Bootstrapped Pearson's correlation coeff. = 0.82, 95% CI = 0.588–0.937).

Power Analysis for Presence or Absence

Automated acoustic monitoring exceeded a 90% mean likelihood of detecting murrelets after 10 mornings of acoustic monitoring at all 7 sites. In general, sites with lower activity levels required a greater number of surveys in order to achieve a 90% likelihood of detecting presence (Fig. 3).

Cost Estimates

The cost of monitoring 7 sites with acoustic sensors, including staff time for analysis, and long-term data storage, was estimated at US$7,780 (US$1,111/site) with purchasing acoustic sensors. Assuming a 10-year monitoring program (and a 10-year life of equipment), with equipment investment spread across years, automated acoustic monitoring costs US$427/site/year. Previous contracts in the Santa Cruz Mountains have cost approximately US $432/survey to conduct human audio–visual surveys (P. Halbert, personal communication). Given the norm of 3 surveys/year, the cost of site per year is approximately US $1,296, or US$9,072 for 7 sites.

DISCUSSION

This study provides more evidence that automated sensors are a powerful tool for wildlife monitoring, by increasing the temporal and spatial scale of sampling and reducing biases (Gauthreaux and Belser 2003, Porter et al. 2005, Rovero and

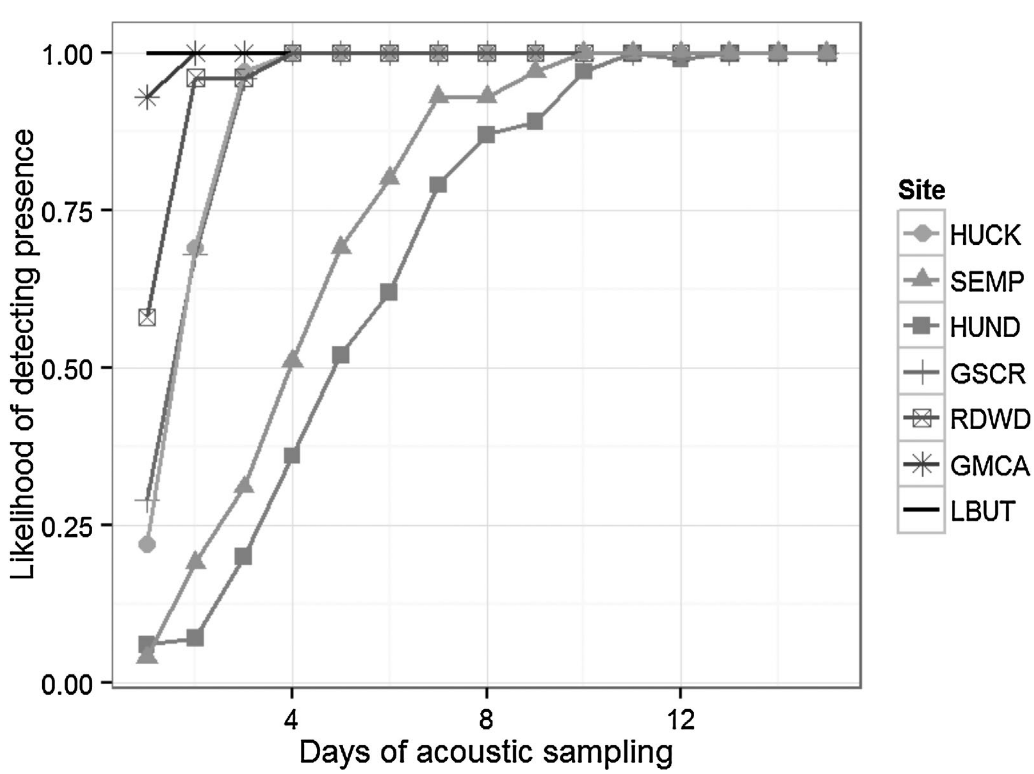

Figure 3. Likelihood of detecting marbled murrelets after successive days of automated acoustic monitoring during the 2010 breeding season, at 7 sites in the Santa Cruz Mountains, California, USA. Shading is ranked from lowest levels of activity (light gray) to highest levels of activity (black) as measured by human surveyors. Symbols denote different sites. GMCA, Gazos Camp; GSCR, Girl Scout Creek; HUCK, Huckleberry; HUND, 100 Acre Woods; LBUT, Little Butano Creek; RDWD, Redwood Meadow; SEMP, Sempevirens.

Marshall 2009). Passive acoustic monitoring of vocal wildlife is a scalable solution for achieving monitoring goals (Grava et al. 2008, Blumstein et al. 2011, Borker et al. 2014), and has proven effective with rare and elusive species (Wade et al. 2006, Thompson et al. 2010). Removal of a human observer comes with some statistical and cost advantages, but no microphone will match the ecological insights to be gained from a human observer. Our results indicate that compared with traditional surveys, automated acoustic sensors detected fewer murrelets during each morning, but greatly expand the number of mornings that can be sampled and the total number of murrelet detections at the seasonal scale for a comparable cost. At a broad scale, detecting the presence of marbled murrelets is important to prioritize areas for occupancy surveys and potential management actions. Both traditional and acoustic methods succeeded in detecting murrelets at all sites in the study. Given the relatively high cost of human surveys, and the ineffectiveness of a single survey to suggest probable absence, automated acoustic recording seems a promising technique to survey large remote areas for murrelets.

Acoustic monitoring had an 80% likelihood of detecting murrelet presence by 8 mornings, even at sites with low levels of murrelet activity. These results suggest that sensors could be moved across sites throughout a season to survey multiple sites for detecting presence, providing potential cost savings. The inland forest survey protocol has set a standard of 5 audio–visual surveys to determine murrelet presence, costing an estimated US$1,400–2,160. Comparatively, near-continuous acoustic sampling of a site throughout the entire breeding season could cost US$1,111, or less if part of a larger or longer term monitoring program. Bigger et al. (2006*a*) reported a less costly US$280/survey in northern California, but did not include costs of data management and report writing.

Although acoustic monitoring was able to detect murrelets at all sites, it barely managed to do so at 2 sites with <5 detections. At both those sites audio–visual surveyors only detected murrelets on one of the 3 surveys. Given limited budget and unlimited time, acoustic sensors may provide a more effective tool for detecting presence. However, ignoring expense, repeated audio–visual surveys would provide the fastest way to assess murrelet presence at very low activity sites, because they achieve higher rates of detection given an equal number of mornings sampled. Activity levels measured by human surveyors and acoustic sensors were highly correlated. At a given sampling effort (mornings), human observers consistently detected more murrelets.

The potential utility of autonomous sensors and analysis for detecting threatened species is promising, because staff and financial resources are a major limitation in all monitoring programs. Furthermore, costly monitoring can divert resources from important conservation actions. For murrelets, acoustic sensors could be widely applied over large areas of suspected breeding habitat to survey areas for presence and probable absence. Acoustic monitoring results could guide intensive surveys for determining occupancy, which is currently delineated mainly by visual cues and very rare acoustic events (Mack et al. 2003). Future directions should include comparing acoustic activity at occupied and unoccupied breeding sites, and trying to detect rare acoustic signs of breeding occupancy. Ongoing studies have used acoustic tools to measure seabird abundance, phenology, and breeding occupancy (Buxton and Jones 2012, Borker et al. 2014). Seasonal patterns of acoustic activity at occupied sites should be investigated as an indicator of breeding effort where breeding phenology is independently measured. Finally, a watershed-scale network of sensors might be used to identify areas of high calling activity and gradients, identifying potential nesting areas. Acoustic activity across a watershed could be paired with radar monitoring to evaluate acoustic indices of abundance.

Unlike traditional human audio–visual surveys that produce no permanent record, acoustic sensors created $>1,000$ hr of acoustic recordings that can be reanalyzed and interpreted as new questions arrive. By allowing reanalysis of archived data sets, these data streams eliminate inter- and intra-observer biases. Compared with human surveys, an entire season of acoustic recordings can be collected at minimal cost, and sensors can be deployed in remote areas not accessible by trained observers for multiple human or radar surveys.

Further study is needed to examine the relationship between acoustic activity and breeding status, but sites with acoustic detections could be prioritized for human surveys that can be used to establish occupancy. This could greatly expand the inland surveying effort for murrelets on a fixed budget. Monitoring at inland sites is important because murrelets have sensitive breeding requirements and are threatened by habitat loss and habitat management (Peery et al. 2004, Raphael et al. 2013). Actions that affect breeding habitat (including timber harvest or predator control) should be evaluated at those sites and compared with inland controls to identify the most effective actions for conservation and for mitigation of impacts.

The application of passive acoustic monitoring to marbled murrelets is promising. Despite lower detection rates during simultaneous audio–visual surveys and acoustic recordings (likely to be improved with new analysis tools), automated sensors consistently detected more murrelets by sampling >10 times more mornings than human surveyors, at less than a fifth of the cost.

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LITERATURE CITED

Bigger, D., M. Z. Peery, J. Baldwin, S. Chinnici, and S. P. Courtney. 2006*a*. Power to detect trends in marbled murrelet breeding populations using audiovisual and radar surveys. Journal of Wildlife Management 70:493–504.

Bigger, D., M. Z. Peery, S. Chinnici, and S. P. Courtney. 2006*b*. Efficacy of audiovisual and radar surveys for studying marbled murrelets in inland habitats. Journal of Wildlife Management 70:505–516.

Binford, L. C., B. G. Elliott, and S. W. Singer. 1975. Discovery of a nest and the downy young of the marbled murrelet. The Wilson Bulletin 87:303–319.

Blumstein, D. T., D. J. Mennill, P. Clemins, L. Girod, K. Yao, G. Patricelli, J. L. Deppe, A. H. Krakauer, C. W. Clark, and K. A. Cortopassi. 2011. Acoustic monitoring in terrestrial environments using microphone arrays: applications, technological considerations and prospectus. Journal of Applied Ecology 48:758–767.

Borker, A. L., M. W. McKown, J. T. Ackerman, C. A. Eagles-Smith, B. R. Tershy, and D. A. Croll. 2014. Vocal activity as a low cost and scalable index of seabird colony size. Conservation Biology 28:1100–1108.

Burger, A. E. 2001. Using radar to estimate populations and assess habitat associations of marbled murrelets. Journal of Wildlife Management 65:696–715.

Buxton, R. T. 2010. Monitoring and managing recovery of nocturnal burrow-nesting seabird populations on recently predator-eradicated Aleutian Islands. Thesis, Memorial University of Newfoundland, St. John's, Canada.

Buxton, R. T., and I. L. Jones. 2012. Measuring nocturnal seabird activity and status using acoustic recording devices: applications for island restoration. Journal of Field Ornithology 83:47–60.

Cooper, B. A., and R. J. Blaha. 2002. Comparisons of radar and audio-visual counts of marbled murrelets during inland forest surveys. Wildlife Society Bulletin 30:1182–1194.

Department of Interior Fish and Wildlife Service. 1992. Determination of threatened status for the Washington, Oregon and California population of the marbled murrelet. Federal Register 57:45328–45337.

Figueroa, H. 2007. XBAT. v5. Cornell University Bioacoustics Research Program, Ithaca, New York, USA.

Gauthreaux, S., Jr., and C. Belser. 2003. Radar ornithology and biological conservation. The Auk 120:266–277.

Grava, T., N. Mathevon, E. Place, and P. Balluet. 2008. Individual acoustic monitoring of the European eagle owl *Bubo bubo*. Ibis 150:279–287.

Mack, D., W. Ritchie, S. K. Nelson, E. Kuo-Harrison, P. Harrison, and T. Hamer. 2003. Methods for surveying for marbled murrelets in forests: a revised protocol for land management and research. Pacific Seabird Group, Marbled Murrelet Technical Committee, Arcata, California, USA.

Malt, J. M., and D. B. Lank. 2009. Marbled murrelet nest predation risk in managed forest landscapes: dynamic fragmentation effects at multiple scales. Ecological Applications 19:1274–1287.

Nelson, S. K. 1997. Marbled murrelet (*Brachyramphus marmoratus*). Account 276 *in* A. Poole, editor. The birds of North America online. Cornell Lab of Ornithology, Ithaca, New York, USA. http://bna.birds.cornell.edu/bna/species/276. doi:10.2173/bna 276

Peery, M. Z., S. R. Beissinger, S. H. Newman, E. B. Burkett, and T. D. Williams. 2004. Applying the declining population paradigm: diagnosing causes of poor reproduction in the marbled murrelet. Conservation Biology 18:1088–1098.

Porter, J., P. Arzberger, H.-W. Braun, S. Gage, T. Hansen, P. Hanson, C.-C. Lin, F. Lin, T. Kratz, W. Michener, S. Shapiro, P. Bryant, and T. Williams. 2005. Wireless sensor networks for ecology. BioScience 55:561.

R Development Core Team. 2011. R: a language and environment for statistical computing. Volume 1. Tertiary R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Raphael, M. G. 2006. Conservation of the marbled murrelet under the Northwest Forest Plan. Conservation Biology 20:297–305.

Raphael, M. G., G. A. Falxa, and J. O'Callaghan. 2013. From trees to seas—marbled murrelet numbers are down. Science Findings 157. U.S. Department of Agriculture, Portland, Oregon, USA.

Rodway, M. S., and H. M. Regehr. 2000. Measuring marbled murrelet activity in valley bottom habitat: bias due to station placement. Journal of Field Ornithology 71:415–422.

Rovero, F., and A. R. Marshall. 2009. Camera trapping photographic rate as an index of density in forest ungulates. Journal of Applied Ecology 46:1011–1017.

The MathWorks. 2010. MATLAB: the language of technical computing v. R2009a. The MathWorks, Natick, Massachusetts, USA.

Thompson, M. E., S. J. Schwager, K. B. Payne, and A. K. Turkalo. 2010. Acoustic estimation of wildlife abundance: methodology for vocal mammals in forested habitats. African Journal of Ecology 48:654–661.

Van Parijs, S. S. M., C. W. Clark, R. R. S. Sousa-Lima, S. E. S. Parks, S. Rankin, D. Risch, and I. I. C. Van Opzeeland. 2009. Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales. Marine Ecology Progress Series 395:21–36.

Wade, P., M. P. Heide-Jørgensen, K. Shelden, J. Barlow, J. Carretta, J. Durban, R. LeDuc, L. Munger, S. Rankin, A. Sauter, and C. Stinchcomb. 2006. Acoustic detection and satellite-tracking leads to discovery of rare concentration of endangered North Pacific right whales. Biology Letters 2:417–419.

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SUPPORTING INFORMATION

Additional supporting information (survey site information, cost estimates, and graphical comparison of methods during simultaneous surveys) may be found in the online version of this article at the publisher's web-site.

Figure S1. Map of marbled murrelet monitoring stations (both automated acoustic and human surveys) used in this study within the Santa Cruz Mountains, California, USA.

Figure S2. Relationship of automated acoustic and human detections of marbled murrelets on the same 29 mornings across 7 sites the Santa Cruz Mountains, USA. Bootstrapped Pearson's correlation coefficient = 0.82, 95% CI = 0.588–0.937.

Table S1. Locations and full names of marbled murrelet monitoring sites used in this study within the Santa Cruz Mountains, California, USA.

Table S2. Cost estimates for acoustic marbled murrelet monitoring at 7 sites in the Santa Cruz Mountains, USA, for 10 years.