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Techniques for Monitoring *Brachyramphus* Murrelets: A Comparison of Radar, Autonomous Acoustic Recording and Audio-visual Surveys

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JENNA L. CRAGG,[1] *Department of Biology, University of Victoria, P.O. Box 3020 STN CSC, Victoria, BC V8W 3N5, Canada*

ALAN E. BURGER, *Department of Biology, University of Victoria, P.O. Box 3020 STN CSC, Victoria, BC V8W 3N5, Canada*

JOHN F. PIATT, *United States Geological Survey, Alaska Science Center, 4210 University Drive, Anchorage, AK 99508-4626, USA.*

[1] *E-mail: jenna.cragg@gmail.com*

ABSTRACT Conditions in Alaska, USA, pose a challenge for monitoring populations of *Brachyramphus* murrelets using standard census methods, because of strong winds, 2 sympatric species, short nights, and variable nesting habitat. We tested 3 methods for monitoring *Brachyramphus* murrelets breeding in the Kodiak Archipelago, Alaska, in 2010–2012. In addition to standard audio-visual and radar methods, we tested—for the first time with murrelets in Alaska—the application of autonomous acoustic recorders for monitoring vocal activity. We completed 74 radar, 124 audio-visual, and 134 autonomous acoustic surveys, focused on presunrise activity peaks; this yielded 26,375 murrelet detections. Marbled (*B. marmoratus*) and Kittlitz's murrelets (*B. brevirostris*) could not be distinguished using combinations of radar and acoustic recordings; therefore, at-sea surveys will be required to determine localized species proportions. Of the 3 methods, radar sampled the largest area and detected silently flying murrelets, providing the most reliable data on local populations; however, radar identification of murrelets was unreliable in winds exceeding 18 km/hour. Audio-visual surveys were useful for species identification and to document behaviors associated with local nesting, whereas autonomous acoustic recorders allowed season-long monitoring of murrelet vocal activity. Within potential forest-nesting habitat of marbled murrelets, all 3 methods gave similar measures of presunrise murrelet activity, but only radar reliably sampled murrelets commuting between nest and ocean. Because of their low cost and flexible programming, automated sound recorders offer an affordable way to sample vocal activity prior to more intensive or expensive radar and audio-visual surveys. We recommend that population monitoring and habitat studies of *Brachyramphus* murrelets in Alaska include combinations of all 3 methods.

KEY WORDS Alaska, audio-visual, automated acoustic recording, *Brachyramphus* murrelets, Kittlitz's murrelet, marbled murrelet, population monitoring, radar.

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Marbled murrelets (*Brachyramphus marmoratus*) have an extensive breeding range that extends from central California through the Aleutian Islands of the United States. Their congener, the Kittlitz's murrelet (*B. brevirostris*), has a more restricted range in Alaska, USA, and eastern Russia, and the 2 species of diving seabirds breed sympatrically in parts of Alaska. *Brachyramphus* murrelets are unique among alcids (Alcidae) in their noncolonial and highly dispersed nesting, cryptic breeding sites, camouflaged plumage and secretive nest attendance. These nesting habits make it difficult to census and monitor populations, yet both species of *Brachyramphus* murrelets are of conservation concern in Alaska as a result of evidence of large population declines over the past 25 years (Piatt et al. 2007, 2011; Kuletz et al. 2011*a*, *b*). Reliable census methods for murrelets are needed in Alaska to refine population estimates, establish long-term monitoring programs and undertake habitat association studies.

Throughout their range, marbled murrelets generally nest in mossy limbs of old-growth conifers, but also nest on the ground or on mossy cliff ledges (Nelson 1997, Willson et al. 2010, Barbaree et al. 2014). In Alaska, 97% of their at-sea distribution during the breeding season occurs adjacent to forest habitat (Piatt and Ford 1993), but recent evidence suggests that these birds may not necessarily nest in trees (Barbaree et al. 2014); in the Kodiak Archipelago, large populations of murrelets were associated with unforested habitats (Cragg 2013).

Currently, at-sea vessel surveys are the primary methods used in abundance monitoring for *Brachyramphus* murrelets in Alaska (Piatt et al. 2007), but this method gives imprecise population estimates and has low power to detect population trends (Kissling et al. 2007, Kissling 2011). In the southern portion of the marbled murrelet's range, audio-visual and radar surveys are the principal census and monitoring methods (Evans Mack et al. 2003, Bigger et al. 2006*b*, Manley 2006). Radar surveys are used to count flying murrelets as they commute daily between marine foraging habitat and nest sites along predictable flight paths, providing an estimate of the local breeding population size. Audio-visual surveys are designed to monitor murrelet presence and relative abundance within potential nesting habitats and to detect behaviors indicative of nearby nesting. Radar surveys have not been widely tested in Alaska because of conditions that make standard survey methods more challenging than in southern latitudes, including the presence of 2 sympatric species that are not easily distinguished, reduced period of darkness at night, windier conditions, and highly variable nesting habitat.

Automated acoustic recorders can operate unattended in remote locations for weeks to months and have proved successful in population and community studies of other seabirds (Buxton and Jones 2012, Borker et al. 2014, Oppel et al. 2014). A major limitation of monitoring murrelet populations using radar or audio-visual surveys is the high cost of supporting field crews, which often reduces spatial and temporal replication of surveys. Automated acoustic recording devices offer an affordable alternative for season-long monitoring with minimal field logistics, but their effectiveness with *Brachyramphus* murrelets is unknown.

Here we compare daily and seasonal detection rates of murrelets with the 3 methods (radar, audio-visual, and automated acoustic recorders), covering both nesting habitat and commuting flyways (flight paths used daily by murrelets to travel between nest sites and marine foraging grounds; Burger 1997). We compare the strengths and limitations of each method for different aspects of *Brachyramphus* murrelet population management, from monitoring vocal activity in small patches of forest to region-wide population monitoring programs. Although focused on Alaskan conditions, our study has relevance for censusing and monitoring *Brachyramphus* murrelets throughout their ranges.

STUDY AREA

We observed murrelets at 27 sites in the Kodiak Archipelago, Alaska, from 2010 to 2012 (Fig. 1; Cragg 2013). We sampled terrestrial habitats along an ecological gradient from tundra ecosystems typical of subarctic Aleutian Heath on southwestern Kodiak Island (Grant Lagoon; 57°28′N, 154°39′W) to sites dominated by Sitka spruce (*Picea sitchensis*) forests on the northeastern Kodiak Archipelago (e.g., Monashka Bay; 57°50′N, 152°28′W). Both Kittlitz's and marbled murrelets are known to breed in the Kodiak Archipelago (Piatt and Ford 1993, Stenhouse et al. 2008, Lawonn 2013), but Kittlitz's murrelets were rare in our study area, both at sea (≤1% of all *Brachyramphus* murrelets observed at sea; Cragg 2013), and in our inland counts (details below). Consequently we focus our analysis on data from marbled murrelets but provide recommendations for population monitoring applicable to both species of murrelets in Alaska.

METHODS

We conducted repeated radar and audio-visual surveys at Grant Lagoon in 2010 throughout the breeding season to assess diurnal and seasonal activity trends and the effects of weather conditions on radar counts. In 2011 and 2012, we conducted repeated radar, audio-visual, and acoustic surveys simultaneously at Monashka Bay. We sampled an additional 5 sites once each by radar and acoustic surveys in 2012 to compare with results from Monashka Bay. We used counts from radar surveys conducted in 2011–2012 at 21 additional sites in the eastern and the northern Kodiak Archipelago to assess diurnal activity patterns (Fig. 1). All procedures were approved by the University of Victoria Animal Care Committee (protocol 2010-014). Sampling spanned the core breeding period (including incubation, chick-rearing, and fledging), from early June through mid-August, in each year.

Field Methods

We used a marine radar to observe flying murrelets (Hamer et al. 1995, Burger 1997). The radar unit (Furuno 1954C, X-band, 12-kW transmitter, 9,410-MHz, 2-m scanner; Furuno Electric Co., Ltd., Nishinomiya, Hyōgo Prefecture, Japan) had been modified by tilting the scanner upward by 15° according to standard adjustments for murrelet surveys (Burger 1997, Harper et al. 2004). In 2010 at Grant Lagoon, we conducted exploratory surveys of 6 hours in randomized periods throughout the 24-hour cycle to investigate diurnal activity and to permit visual identification during daylight of other species detected by radar. We found commuting murrelets were active throughout the night, with a peak of activity that began 2 hours before sunrise (Cragg 2013). Thus, in 2011–2012, we conducted radar surveys only at night, beginning 30 minutes before sunset and ending 1 hour after sunrise or 10 minutes after the last murrelet detection, whichever came last (sunrise and sunset times from www.sunrisesunset.com).

For each murrelet detected by radar, we recorded flight behavior in an attempt to distinguish murrelets from other species. We identified targets (Fig. 2A) on the basis of 4 criteria: 1) flight speed ≥50 km/hour; 2) flight type (direct or sinusoidal); 3) flight path consistent with the likely route used for commuting flight between potential nesting areas and marine foraging sites; and 4) ≥4 sequential images of the target (hits). If all 4 criteria were met, we recorded the target as a 'murrelet'; we recorded targets meeting fewer than 4 of the criteria as an unknown species. We recorded the actual species if verified by the audio-visual observer (see below). We categorized murrelet flight direction shown on radar as inbound (landward) or outbound (seaward). We recorded weather conditions (wind speed, measured with an anemometer; and wind direction, measured by compass) at the start and end of each survey, plus weather events during the survey that would affect the reliability of data (e.g., high winds or rain showers). Rain showers produce screen clutter on radar that reduces visibility of bird targets; therefore, if rain persisted for >10 minutes during peak activity periods (2 hr presunrise), the survey data were not used in analyses.

We conducted audio-visual surveys in conjunction with radar surveys at dusk (from radar survey start until civil twilight) and at dawn (1 hr before sunrise until 1 hr after sunrise). We used standard audio-visual protocols (Evans Mack et al. 2003) to record murrelet detections, including species identity when possible, and behaviors indicative of potential nesting nearby (i.e., flight below the forest canopy, aerial dives, and low-altitude circling).

We deployed Song Meter automated acoustic sensors (Wildlife Acoustics, Inc., Concord, MA; SM1, SM2 Terrestrial and Night Flight; see Cragg et al. [2015] for details on model performance) during the murrelet breeding season (Jun–Aug) in 2011 and 2012. Recordings were analyzed using automated recognition models developed in Song Scope acoustic software (Wildlife Acoustics, Inc.) that identified potential murrelet vocalizations within recordings, which were then checked by a human observer on a spectrogram and grouped into call types according to Dechesne (1998). Details of field sampling and acoustic analysis are in Cragg et al. (2015). Song Meters were programmed to record for 2 hours each day, starting 2 hours before sunrise, to match the peak of murrelet activity observed by radar.

At Monashka Bay, we deployed Song Meters in 2011 and 2012 within forested potential nesting habitat (sensors FOR1 and FOR2, located in the same tree to compare sensor performance; Cragg et al. 2015) and along an unforested flight path used by murrelets identified by radar (FP; Fig. 2B). For testing differences among other sites, in 2012 we deployed sensors at 6 sites in the northern Kodiak Archipelago in potential forested nesting habitat within the radar scanning areas (Fig. 1); at one site no forested nesting habitat was available and we placed the Song Meter below a commuting flight path. Multiple Song Meters could be used within one radar-station scanning radius because of the much smaller area sampled by Song Meter (60-m radius; Cragg et al. 2015) compared with the radar-scanning radius (1.5 km).

Definitions of Detections

The murrelet 'detection' was the common unit of comparison among survey methods. In radar surveys, a murrelet detection was defined as a series of ≥4 radar echoes that have the appearance, flight speed, and flight pattern characteristic of a murrelet (Manley 2006). For audio-visual surveys, we defined a murrelet detection as "the sighting or hearing of one or more murrelets acting in a similar manner" (Paton 1995:113), with gaps between calls of >5 seconds considered separate detections (Evans Mack et al. 2003). We similarly defined an automated acoustic murrelet detection as a series of murrelet calls not separated by >5 seconds (Cragg et al. 2015).

Exploring Diurnal and Seasonal Trends and Wind Effects

Only one site provided radar sampling spanning most of a breeding season (Grant Lagoon; 14 overnight surveys, 3 Jun–27 Jul 2010). We used mean murrelet counts per hour for each survey to show seasonal trends in activity (Table 1A). We also used these repeated counts to test whether increasing wind speed resulted in higher counts of murrelet targets (due to apparently greater flight speed of birds caused by tailwinds) using linear regression ($\alpha = 0.05$ for all statistical tests). We then removed outlier counts from wind events exceeding approximately 18 km/hour from the linear regression to assess whether the trend remained significant. Despite the relatively open and exposed coastline of the Kodiak Archipelago, high winds (>18 km/hr) did not affect a high proportion of surveys across all sites (11.1% of all surveys attempted in 2010–2012), whereas high winds prevented only 3 survey attempts. We did not use data from surveys affected by high winds in other analyses.

To examine diurnal activity patterns in radar and audio-visual surveys at all other sites in 2011 and 2012, we calculated the proportion of murrelets flying inland in each survey's counts within 30-minute intervals (relative to sunrise), calculated the mean proportion in each interval across all sites, and used the coefficient of variation of the mean as a measure of variability in activity (Table 1B). We used mean counts per hour at Grant Lagoon rather than using counts of murrelets flying inland per 30-minute interval presunrise, because of the low counts at this station.

We made season-long tests of Song Meters within the radar scanning area at Monashka Bay on Kodiak Island, at 2 locations from 15 June to 3 September 2011, and from 1 June to 27 August 2012 (Table 1C; Fig. 2B). To illustrate similarities in seasonal activity trends, and to demonstrate differences in seasonal coverage by different survey methods, we plotted repeated counts for the 3 survey methods across the breeding season from Grant Lagoon (radar; 2010), and Monashka Bay (radar, audio-visual, and Song Meter; 2011–2012) using local polynomial regression fitting.

Comparison Between Radar, Audio-visual, and Autonomous Acoustic Detections

We compared audio-visual and Song Meter detections for surveys conducted at Monashka Bay, which was the only location where audio-visual observers were within 300 m of the Song Meter. We conducted simultaneous surveys on 6 mornings in both 2011 (10–18 Jul) and 2012 (16–24 Jul). We compared the total number of audio-visual detections with Song Meter detections during the period starting 1 hour before sunrise when surveys overlapped (Table 1D). We compared total audio-visual detections (visual and aural) with acoustic recordings rather than comparing only aural detections (ignoring visual observations) to assess whether acoustic sensors provided detection frequencies comparable to a human observer. The 2011 data were collected slightly earlier in the season and had lower overall counts than 2012; therefore, we compared the yearly mean Song Meter and audio-visual counts separately using 2-sample *t*-tests. In addition, we compared counts from radar, Song Meter, and audio-visual surveys in each year for the Monashka Bay site using a one-way ANOVA for the period during which all 3 surveys were conducted simultaneously (1 hr presunrise; Table 1E).

For spatial comparisons, we used radar and Song Meter counts at 6 sites where surveys were conducted in 2012 to test for correlations in counts across sites (Table 1F; Fig. 1). The goal was to compare targets detected by radar that could potentially be detected by a Song Meter; however, because radar surveys focused on counting all flying birds within the scanning radius, it was not possible to track the distance of each target from the Song Meter location. Rather, where obvious flight paths distant (≥500 m) from Song Meter locations were found, we excluded those radar data from comparisons with Song Meter. We compared the frequency of vocal detections from Song Meters (total detections per morning) with the total number of incoming commuting murrelets observed by radar at each site (with the exception of excluded flight paths). We surveyed 5 of the 6 sites only once (Cragg 2013), but we conducted multiple surveys at Monashka Bay. Thus, we used a mean count of daily Song Meter and radar detections from Monashka Bay for this analysis. We tested for correlation between radar and Song Meter detections across the 6 sites using a Spearman's rank test.

We conducted a within-site comparison of radar and Song Meter counts at Monashka Bay, where we repeated concurrent radar and Song Meter surveys on multiple mornings in 2011 and 2012 (Table 1G). To test whether radar and Song Meter counts were correlated, we compared Song Meter counts from the sensor location FOR1 (Fig. 2B) with radar counts for the flight path closest to this sensor using a Spearman's rank test for pooled counts from both years.

To test for on-site habitat effects, we compared differences in vocalization rates recorded by Song Meters in relation to radar counts for Song Meters located in 2 habitat types within the radar scanning area at Monashka Bay: 1) a forested likely nesting area, where 24% of murrelet targets observed by radar (N = 587) engaged in circling flight (suggesting site occupancy; Evans Mack et al. 2003); and 2) a high-traffic commuting flight corridor, where 96% of murrelet targets (N = 926) were commuting (fast direct flight). We compared mean counts between Song Meter and radar in potential nesting habitat (sensors FOR1 and FOR2), and for the commuting corridor (sensor FP) using Welch's 2-sample t-tests (Fig. 2B; Table 1H).

RESULTS

Survey Effort

In 2010–2012, we completed 74 radar surveys (including the dawn activity period and other sampling periods at Grant Lagoon), 124 audio-visual surveys (dawn and dusk), and 134 dawn Song Meter surveys, yielding 26,375 murrelet detections (Table 1). We used subsets of radar surveys for different comparative analyses: 35 surveys throughout the 24-hour cycle at Grant Lagoon to assess diurnal activity patterns in 2010 (Table 1A); 36 overnight surveys to assess diurnal activity trends across 26 sites (2011–2012; Table 1B); and 12 surveys at Monashka Bay for comparison with audio-visual and acoustic surveys (2011–2012; Table 1E–H).

Species Differentiation and Wind Effects

Murrelet targets flew on average 35 km/hour faster than other species visually identified during radar surveys (mean murrelet flight speed ± SE: 83.0 ± 0.5 km/hr, N = 1,796). Direct or sinusoidal flight paths were most common for murrelets (89.9% of records; N = 2,330), and we observed circling behavior (9.1%) when radar stations were located near forested potential nesting habitat. Differentiation between Kittlitz's and marbled murrelet targets by radar was not possible, even at Grant Lagoon where Kittlitz's murrelet was known to nest (Lawonn 2013). In our pooled data, species identity was confirmed by visual observations for <1% of radar detections (most murrelets appeared as fast-flying silhouettes) and all murrelet vocalizations recorded were by marbled murrelets.

Audio-visual surveys were useful in identifying species that could be confused for murrelets on radar, such as red-throated loons (*Gavia stellata*), mergansers (*Mergus* spp.), cormorants (*Phalacrocorax* spp.), and eagles (*Haliaeetus leucocephalus*); however, audio-visual observers were unable to determine the species identity of the majority of murrelet targets on radar. Over the 3 field seasons and >200 hours of observation, no Kittlitz's murrelets were positively identified by audio-visual surveys. All audio-visual detections summarized in this study (N = 2,239) were of marbled murrelets or unidentified *Brachyramphus* murrelets. Audio-visual detections were greatest where murrelets engaged in social interaction near potential forest-nesting habitat, producing 653 detections of behavior indicative of nearby occupancy of nest sites ('occupied detections'; Evans Mack et al. 2003).

Automated acoustic sensors recorded 4 types of marbled murrelet vocalizations and 2 nonvocal sounds (wing beats and jet sounds), yielding 5,870 detections. No Kittlitz's murrelet vocalizations were detected over 134 surveys (268 hr of recordings).

High winds limited the reliability of using flight behavior to differentiate murrelets from other species with radar. Strong tail winds increased flight speeds of all birds and head winds reduced them; in either case, differentiating murrelets from slower flying birds became problematic. In 2010 surveys at Grant Lagoon, we observed a positive relationship between murrelet counts and wind speed ($F_{1,17}$ = 10.94, R^2 = 0.39, P = 0.004). However, when we removed high wind events (>18 km/hr) from the analysis, the relationship was no longer significant ($F_{1,15}$ = 0.083, R^2 = 0.01, P = 0.78).

Diurnal and Seasonal Activity Patterns

Diurnal activity patterns observed by radar showed murrelet activity peaks at dawn (1.0 hr presunrise, mean ± SE of 27.3 ± 0.7% of total detections, N = 36; Fig. 3) and dusk (5.5 hr presunrise, 3.7 ± 0.3% of detections, N = 35). Dawn counts were both higher and had a lower coefficient of variation (CV = 38%) than dusk counts (CV = 81%). Landward flight activity peaked 84 ± 3 minutes (N = 49) before sunrise, whereas seaward flight activity peaked 48 ± 6 minutes presunrise (N = 47). Diurnal activity patterns at Grant Lagoon differed from those at sites with greater murrelet abundance. At Grant Lagoon, a prolonged period of relatively constant activity began at sunset (6 hr presunrise) and lasted until 2 hours postsunrise, with the mean proportion of total activity dispersed throughout the night (ranging from 7.0% to 15.9% of all activity; mean ± SE of 11.1 ± 0.8%). In contrast, at other sites, activity was concentrated at dawn (2 hr presunrise–1 hr postsunrise), accounting for 82.3 ± 2.3% of all detections, with very little activity occurring before this period (mean of 4.4 ± 0.8% of detections/hr).

Comparing seasonal activity across all 3 survey methods, there was a consistent trend in increased activity through June and July, with a peak of activity occurring in late July, followed by a decline through August (Fig. 4).

Comparison Between Radar, Audio-visual, and Autonomous Acoustic Detections

There was no difference in annual mean counts of all detections between audio-visual (AV) and Song Meter (SM) surveys in 2011 (mean ± SE: AV = 56.3 ± 11.5, SM = 77.5 ± 8.9; 2-sample t-test; t = 1.453, df = 10, P = 0.177) or 2012 (mean ± SE: AV = 109.0 ± 9.0, SM = 100.0 ± 11.2; t = 0.569, df = 10, P = 0.582). Although there was no difference in annual mean counts between survey methods, daily counts from the 2 methods were not correlated when detections from both years were pooled (S = 168, r_s = 0.41, P = 0.185).

Radar detected more murrelets during dawn surveys than either audio-visual or automated acoustic methods, when all flight paths were considered, primarily during dark twilight (Fig. 3). However, when all 3 survey methods were compared in likely nesting habitat at Monashka Bay (excluding distant radar flight paths), there was no difference in mean presunrise counts (one-way ANOVA; $F_{2,27} = 0.579$, $P = 0.567$), although audio-visual and Song Meter counts had higher variance (Fig. 5).

In addition to similar presunrise counts, similar behavior was observed between radar and audio-visual surveys: there was no difference in the mean number of circling murrelets observed between radar (mean ± SE: 38.1 ± 7.6/survey) and audio-visual surveys (33.4 ± 7.1/survey) for pooled counts from 2011 and 2012 at Monashka Bay (Wilcoxon signed-rank test; $V = 59.5$, $P = 0.683$). Song Meter detections did not provide information on the flight behavior of murrelets, with the exception of rare detections of wing beats and jet sounds (0.2 detections/hr, $N = 148$ hr). By comparison, audio-visual surveys detected site-occupancy behaviors (below-canopy flight, circling, aerial dives; Evans Mack et al. 2003) on average 18 times/hour ($N = 26$ hr).

The greatest difference between radar and audio counts was along a commuting flight path at Monashka Bay (where no audio-visual surveys were done); commuting murrelets were generally silent, and radar counts averaged 11 times higher than Song Meter counts (mean ± SE = 174.4 ± 11.8 radar detections; 16.0 ± 1.3 Song Meter detections). In contrast, there was no significant difference between the mean number of radar and Song Meter detections in likely forest-nesting habitat (mean ± SE = 103.6 ± 6.8 radar detections; 95.4 ± 2.7 Song Meter detections; $t = 0.563$, df = 11.8, $P = 0.584$). Although mean counts did not differ at Monashka Bay, there was no correlation between Song Meter and radar counts in potential nesting habitat across the breeding season, from pooled 2011 and 2012 surveys ($S = 111.8$, $r_s = 0.32$, $P = 0.364$). There was also no correlation between radar and Song Meter counts made at 6 sites sampled in 2012 ($S = 8$, $r_s = 0.77$, $P = 0.103$), even when data from one outlier site were removed ($S = 2$, $r_s = 0.90$, $P = 0.083$). However, our sample size was small ($N = 10$ within site, $N = 6$ comparing across sites), which greatly reduced our power to detect a correlation.

DISCUSSION

Diurnal Activity Patterns

Diurnal activity trends described by radar surveys on Kodiak Island (57°N) showed that commuting murrelets were active earlier and for longer periods (peak of activity beginning 120 min before sunrise and lasting 150 min) relative to sunrise, compared with populations at lower latitudes. In British Columbia, Canada, and Washington, USA (47–49°N), activity peaks recorded with radar typically began 60 minutes before sunrise and lasted 60 minutes (Burger 1997, 2001; Cooper et al. 2001). Similarly, vocal activity detected by acoustic sensors and audio-visual surveys peaked in the hour preceding sunrise, earlier than activity peaks in southeastern Alaska (S. K. Nelson, Oregon State University, personal communication) and south of Alaska (Rodway et al. 1993, Naslund and O'Donnell 1995). Patterns of activity at high latitude corresponded to earlier civil twilight and longer twilight periods, suggesting that murrelets respond to light cues in timing their inland flight activity. Protocols for monitoring populations of murrelets should therefore be adjusted with earlier start times at higher latitudes to account for longer twilight and activity periods of murrelets (Naslund and O'Donnell 1995). At the latitude of the Kodiak Archipelago this corresponds to starting radar surveys 120 minutes presunrise, 30 minutes earlier than standard protocols established in British Columbia (Manley 2006).

Seasonal Activity Patterns

Logistical and funding constraints prevented sampling throughout the entire breeding season by radar and audio-visual methods, whereas automated acoustic sensors provided the most complete seasonal coverage in 2011 and 2012. All 3 survey methods showed similar timing of seasonal trends in activity. The increased murrelet activity in mid-July, recorded by all 3 survey methods, indicates an increase in murrelets commuting to the nesting habitat (evidence from radar counts), as well as more vocal activity during this phase of the breeding season (evidence from Song Meters and audio-visual surveys). These trends reflect the timing of phases in breeding chronology (Hamer and Nelson 1995, Kuletz 2005), where peak activity corresponds to the onset of chick-rearing and early fledging stages. South of Alaska from California to British Columbia, seasonal trends have been detected in some cases by radar (Cooper et al. 2001) and audio-visual surveys (reviewed in O'Donnell et al. 1995); however, no seasonal trends were observed in other studies restricted to the core periods of the breeding season (Jodice and Collopy 2000, Burger 2001). The clear seasonal activity trend in high-latitude murrelet populations highlights the need for monitoring protocols to factor in seasonal changes in abundance, either by keeping monitoring consistent within similar periods of the breeding season (low activity vs. high activity) or by sampling across the breeding season in each year. Autonomous acoustic monitoring could provide a useful and inexpensive way to identify the seasonal activity patterns in different areas to inform the timing of radar surveys for monitoring populations.

Comparison of Methods: Strengths and Limitations

Radar, audio-visual, and automated acoustic surveys provide information on the relative abundance and behavior of murrelets at 3 scales of activity: commuting flight (away from nesting habitat), near or above nesting habitat, and at the nest site. Of the 3 methods tested, radar detected much higher numbers of murrelets flying silently on commuting flyways over habitat unsuitable for nesting. Both acoustic sensors and audio-visual observers recorded activity above or near nesting habitat, whereas only audio-visual observations could identify likely nesting behaviors.

Our study confirms the superiority of radar as a method for censusing and monitoring populations of breeding murrelets. Radar sampled a much larger area (1.5-km radius compared with approximately 200 m for audiovisual and 60 m for Song Meters; Evans Mack et al. 2003, Cragg et al. 2015) and radar counts had lower variance than audio-visual or automated acoustic surveys (Burger 1997; Cooper et al. 2001; Cooper and Blaha 2002; Bigger et al. 2006*a*, *b*). Radar counts represent an estimate of local-breeding-population size within ‘catchment areas’ or watersheds directly inland of the radar station. These counts have high statistical power to detect population trends (Bigger et al. 2006*a*, Cooper et al. 2006), and provide information on habitat associations in areas where murrelet flight paths are confined by fjords and valleys (Burger 2001, Raphael et al. 2002, Burger et al. 2004). The differences among the methods were accentuated during the dark twilight when few murrelets called and human observers were unable to see flying murrelets. Radar surveys provided more detailed information on flight behavior, including commuting flight direction, circling flight, and spatial patterns over a wide area.

Despite their advantages over other survey methods, radar studies can be limited by low sampling replication (either temporally or spatially) due to cost, logistical constraints, unsuitable topography, and the effects of weather (rain masking radar detections, and unreliable counts during high-wind events). In our comparison, automated acoustic sensors obtained the best seasonal resolution of the 3 survey methods, and at much lower cost than radar surveys (cost per Song Meter unit US$700 and ≤1 hr to process each survey, compared with radar equipment cost of >$10,000 and 5 hr field-crew time/survey). In addition, costs of transporting radar units are also high (heavy, bulky equipment necessitates transport by boat, vehicle, or floatplane). Site access can be difficult in areas with few roads or a lack of suitable anchorages, and radar surveys also require a clear field of view, which can be problematic in forested areas. Other site features such as low topography can be unsuitable for radar counts because murrelet flight paths are dispersed over a wide area (Burger 1997, Raphael et al. 2002). Finally, radar surveys cannot detect below-canopy flight behaviors indicative of nesting, which reduces the likelihood of identifying stand occupancy.

Autonomous acoustic sensor systems can either complement radar studies (e.g., giving greater seasonal coverage) or provide a low-cost alternative to radar surveys for fine-scale assessments of relative abundance and seasonal patterns of vocal activity at localized patches of habitat. The similarity in presunrise rates of detection by all 3 methods at suitable forest-nesting habitat gives support for the use of autonomous recorders for pilot or monitoring studies, provided that the limitations of this method are considered. The similarity in detections by audio-visual and automated acoustic sampling was surprising, given that murrelets were also detected visually by the audio-visual observer and the 2 methods have different sampling radii (approx. 200 m and 60 m, respectively). Two factors might explain the similarity. First, our comparison was confined to the dark twilight hour before sunrise, when visual detections were difficult. Second, our comparison was conducted in high-quality nesting habitat (high densities of potential nest platforms) where murrelets were often observed flying low, circling, and vocalizing frequently. In habitat with fewer potential nest sites or along commuting flyways, murrelets might be less likely to be detected by Song Meters because their vocal behavior may be less conspicuous.

Acoustic sensors are able to detect vocal activity of murrelets near or above nest sites, but cannot consistently detect behaviors indicative of nearby nesting (stand occupancy). Because murrelets are silent at or near their nests, inferences about habitat use (nesting) from indices of vocal activity should be made with caution. Audio-visual surveys, which provide both vocal and behavioral information remain the best method for detecting stand occupancy (local nesting).

MONITORING RECOMMENDATIONS

There is no single ideal method for censusing and monitoring *Brachyramphus* murrelets, particularly in Alaska. Radar surveys provide the most reliable population estimates, but the inability to separate the 2 species with radar and audio methods will require complementary boat surveys in adjacent nearshore waters to estimate the proportions of Kittlitz's and marbled murrelets. Radar surveys on Kodiak Island were correlated with at-sea counts of murrelets within 5–15 km of radar stations (Cragg 2013), but such correlations might not apply where commuting distances between nests and foraging grounds are greater (e.g., 78 km in southeastern AK [Whitworth et al. 2000]; 16 km in Prince William Sound [Kuletz 2005]). Local information on commuting distances and the numerical proportions of the species at sea would improve interpretation of radar censusing.

Boat-based surveys are likely to continue as a monitoring tool in Alaska; therefore, we recommend that radar counts be integrated into these population monitoring programs, using vessels as radar platforms from which to conduct surveys of local breeding populations at suitable shoreline anchorages. Radar surveys should be conducted at carefully selected stations that have suitable topographic features to confine murrelet flight paths along predictable routes to provide the most reliable estimates of abundance, population trends, and habitat associations.

Localized seasonal trend data from automated sensors can be used to inform the timing of radar surveys in subsequent seasons, or can be used to calibrate surveys done within the same season with regard to seasonal activity peaks. Breeding chronology of murrelets can vary between local breeding populations even at the same latitude (McFarlane Tranquilla et al. 2005), potentially affecting the timing of seasonal activity peaks, which is an important factor to consider in timing radar surveys.

For murrelets, combinations of radar, audio-visual, and automated acoustic surveys can be used for different monitoring purposes, providing information on population units and terrestrial habitat associations at finer spatial scales than current at-sea monitoring in Alaska. For example, radar surveys can be used to identify large or important populations of murrelets by censusing flyways into watershed catchment areas (Burger 1997, 2001), followed by assessment of vocal activity within specific habitat patches by acoustic sensors (Cragg et al. 2015). One application of this combination of methods would be to investigate the use of nonforested nesting habitat by marbled murrelets, which may be potentially more widespread than previously assumed in Alaska (Cragg 2013, Barbaree et al. 2014). Acoustic sensors could reduce the need for repeated audio-visual assessments of habitat, by providing an index of murrelet abundance based on vocal activity in the study area that could be followed by targeted audio-visual surveys of the most likely habitat patches to determine occupancy.

The remote nesting locations and sympatric distribution of Alaskan *Brachyramphus* murrelets creates unique challenges for population monitoring and research, yet this region supports the majority of global populations for these 2 threatened seabirds (Gaston and Jones 1998, Piatt et al. 2007). Adding radar, audio-visual, and automated acoustic surveys to regional at-sea monitoring programs will provide greater power to detect population trends and improve knowledge of terrestrial habitat associations.

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Figure 1. Radar and audio-visual sites surveyed for breeding *Brachyramphus* murrelets from 2010 to 2012 in the Kodiak Archipelago, Alaska, USA. Sites with additional automated acoustic surveys are indicated by stars.

Figure 2. A) Radar screen image overlaid over a satellite photo of Monashka Bay, Alaska, USA, showing *Brachyramphus* murrelet targets commuting along a flight corridor in the lower left side of the circle. Large red patches are areas of land detected by the radar scanning beam. Red dots are murrelet targets with echo trails showing their flight path and speed (distance between white dots). B) Locations of Song Meters (FOR1 and FOR2 in likely forest habitat and FP under a commuting flight path) with the scanning radius of the radar (white circle). Typical flight paths are shown by white arrows, with circling occurring above potential forest-nesting habitat and commuting occurring over unforested habitat.

Figure 3. Mean ± standard error detections of *Brachyramphus* murrelets by radar, audio-visual (AV), and Song Meter (SM) surveys relative to sunrise (indicated by arrow). Radar surveys were conducted from 2010 to 2012 in the Kodiak Archipelago, Alaska (USA) beginning 7 hours before sunrise to 1 hour after sunrise, whereas AV surveys began 1 hour before sunrise until 1 hour after sunrise, and SM surveys began 2 hours before sunrise until sunrise (* no AV or SM survey, ** no AV survey, *** no SM survey).

Figure 4. Seasonal trends in detections of *Brachyramphus* murrelets for radar, audio-visual, and Song Meter surveys conducted in the Kodiak Archipelago, Alaska (USA) from 2010 to 2012, with smoothed trend line (local polynomial regression).

Figure 5. Boxplots of simultaneous daily *Brachyramphus* murrelet detections from radar, audio-visual surveys (AV), and Song Meters (SM) during the 1 hour before sunrise in forested habitat at Monashka Bay, Alaska (USA), 2011 and 2012 pooled. Boxplot indicates median and interquartile range; whiskers show minimum and maximum values.

Table 1. Summary of survey method comparisons (radar, audiovisual, and acoustic), survey effort, and locations by year, used for monitoring *Brachyramphus* murrelets breeding in the Kodiak Archipelago, Alaska, USA, 2010–2012. * For this analysis, repeated counts from Monashka Bay were averaged to use one number for comparison with the other 5 sites.

Goal	Survey methods used	Year	Location	Sampling period	No. surveys
A) Explore seasonal and diurnal activity patterns, test effects of wind	Radar	2010	Grant Lagoon	6-hr sampling blocks (24 hr)	35
B) Identify diurnal activity pattern across multiple habitat types	Radar	2011–2012	26 sites in Kodiak Archipelago	30-min presunset until end of dawn activity peak or 1 hr after sunrise	36
C) Identify seasonal and diurnal	Acoustic	2011–	Monashka Bay	2 hr presunrise	134

activity trends		2012			
D) Compare counts in potential nesting habitat	Audio-visual, Acoustic	2011–2012	Monashka Bay	1 hr presunrise	6/yr
E) Compare counts in potential nesting habitat	Radar, Audio-visual, Acoustic	2011–2012	Monashka Bay	1 hr presunrise	6/yr
F) Correlation test of counts across sites	Radar & Acoustic	2011–2012	Monashka Bay & 5 sites in northern archipelago	2 hr presunrise	6*
G) Correlation test of counts at one site across breeding season	Radar & Acoustic	2011–2012	Monashka Bay	2 hr presunrise	10
H) Compare mean counts between potential nesting habitat and commuting flight path	Radar & Acoustic	2011–2012	Monashka Bay	2 hr presunrise	Radar: 10; Acoustic: 34

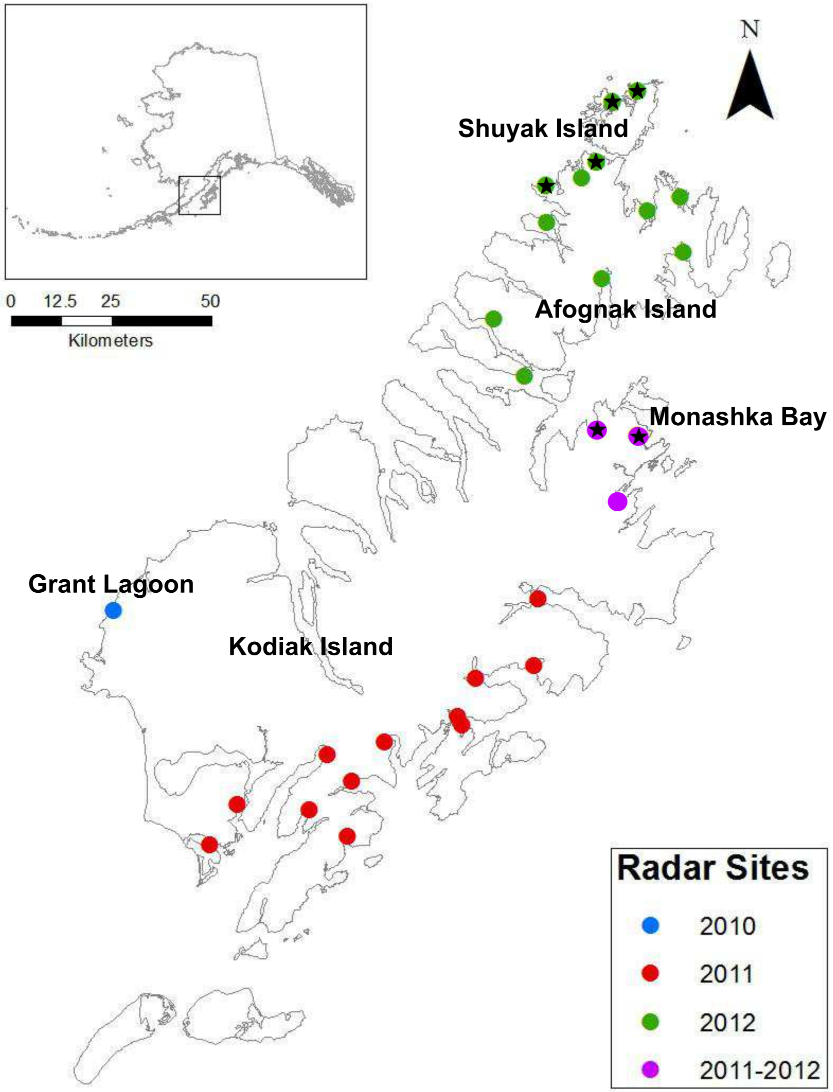

N
0 12.5 25 50
Kilometers
Shuyak Island
Afognak Island
Monashka Bay
Grant Lagoon
Kodiak Island
Radar Sites
2010
2011
2012
2011-2012

Fig1 .

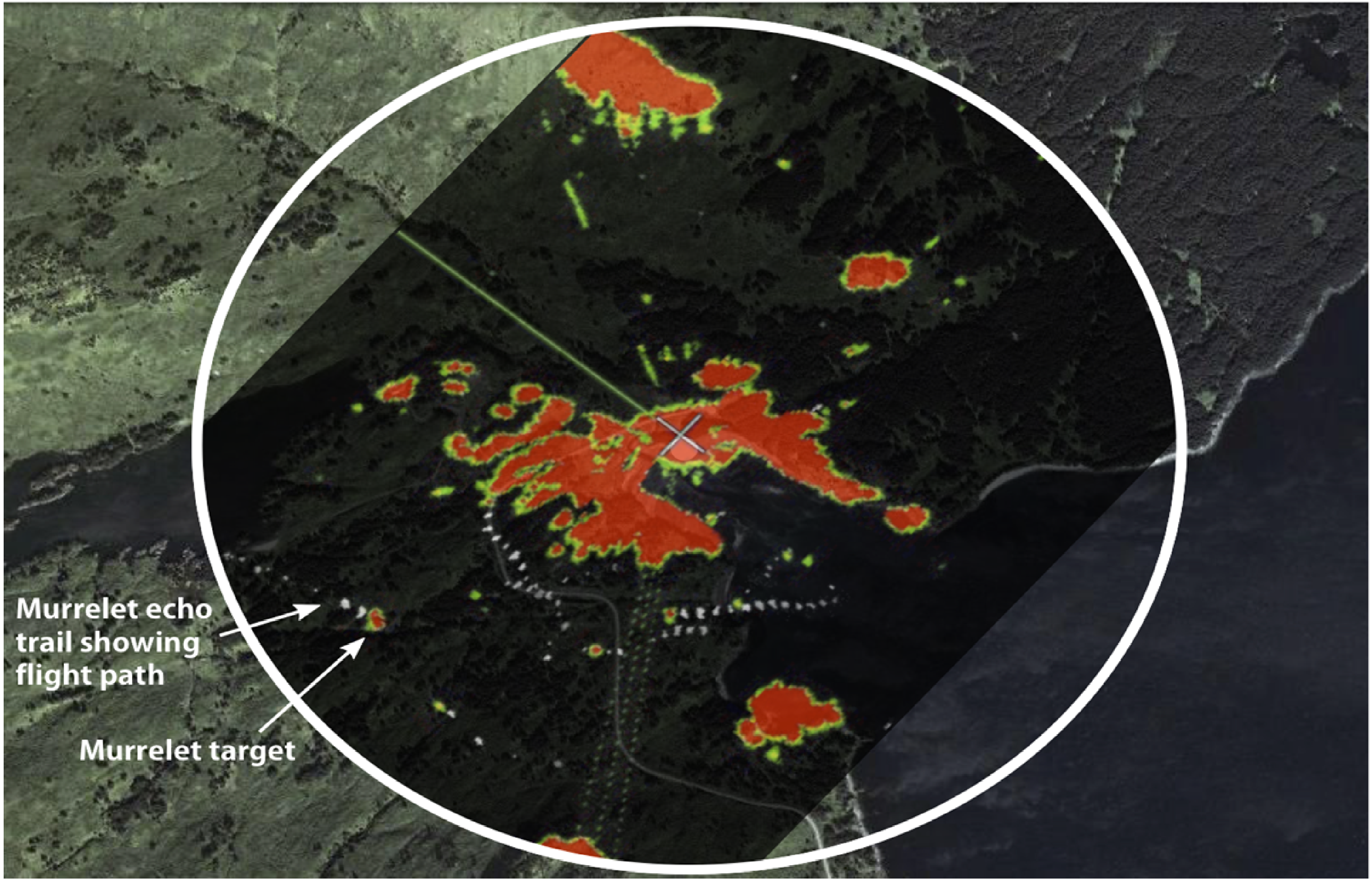

Murrelet echo trail showing flight path
Murrelet target

Fig2A .

Radar & Audio-visual
Song Meter
Flight path
FOR1,2
FP

Fig2B .

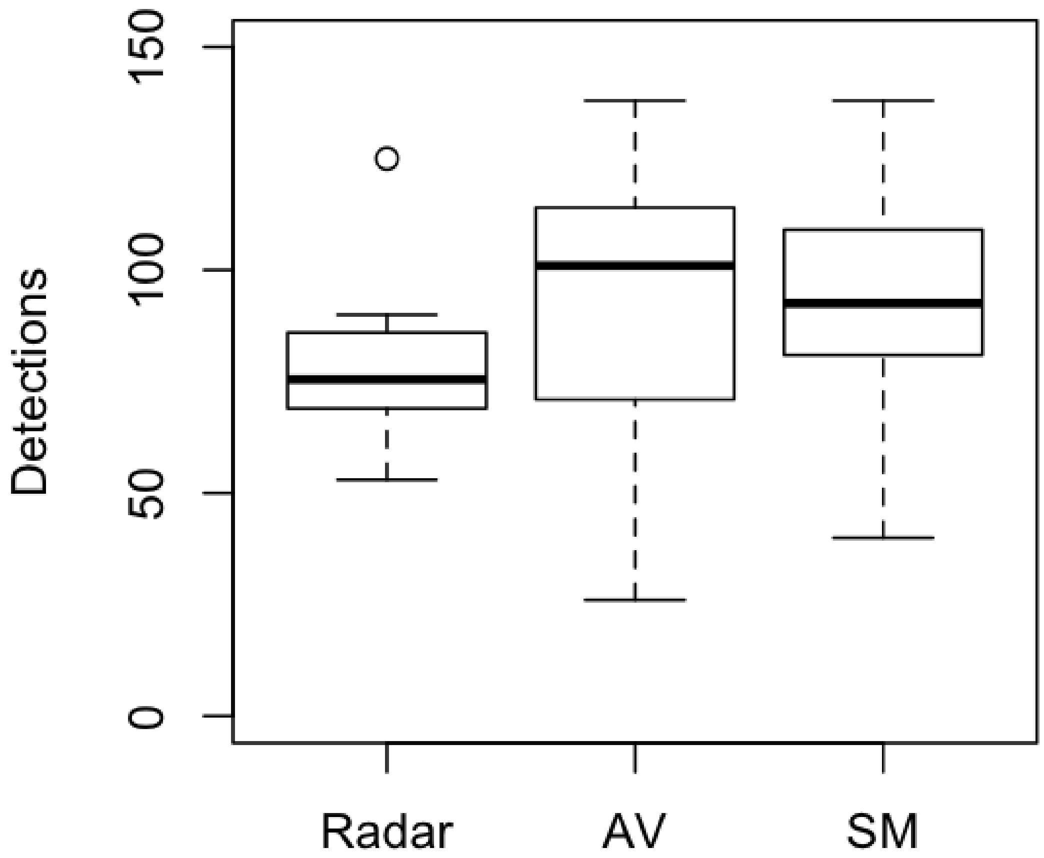
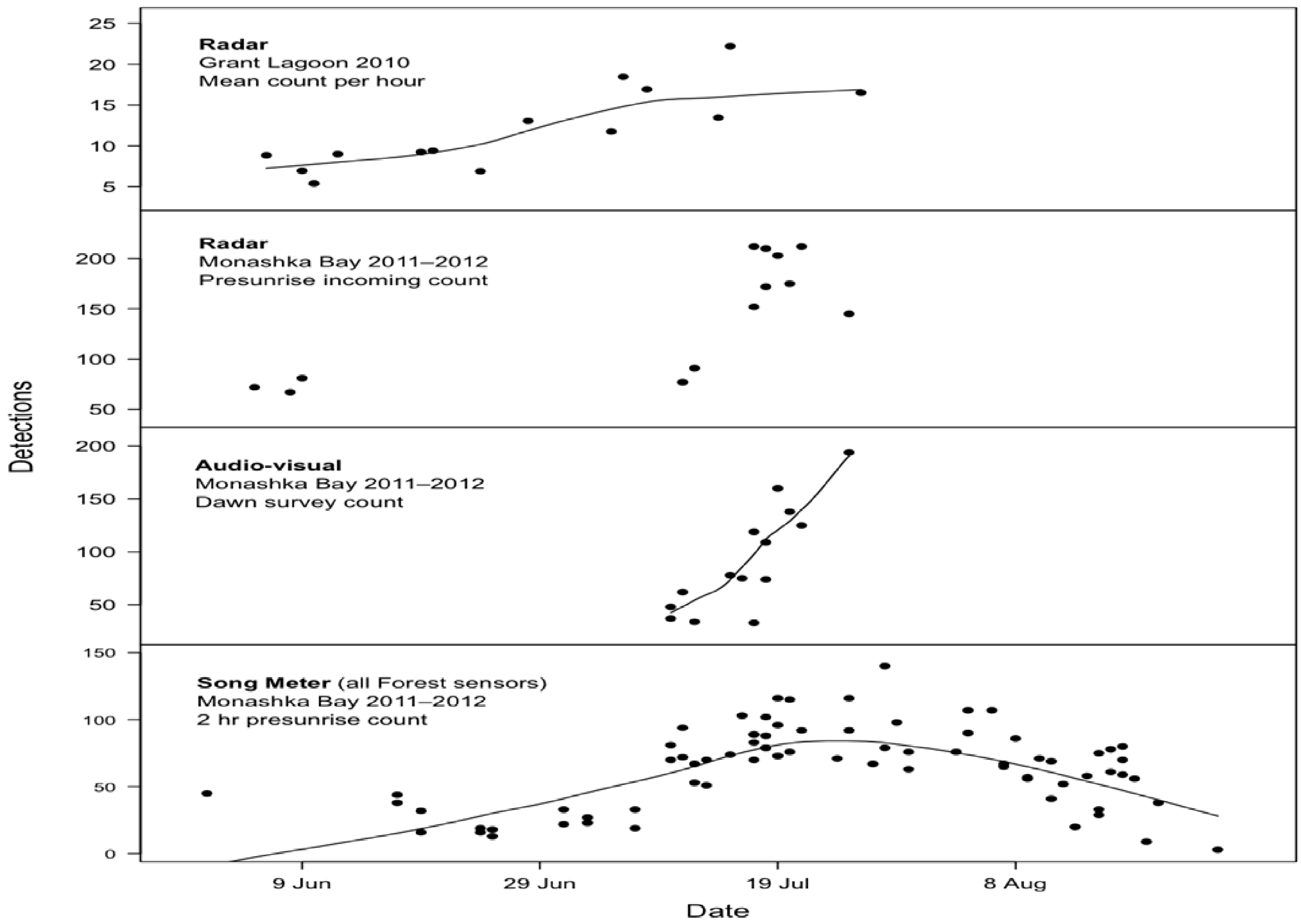


Fig5 .



Radar
Grant Lagoon 2010
Mean count per hour
Radar
Monashka Bay 2011–2012
Presunrise incoming count
Audio-visual
Monashka Bay 2011–2012
Dawn survey count
Song Meter (all Forest sensors)
Monashka Bay 2011–2012
2 hr presunrise count
Detections
Date
9 Jun
29 Jun
19 Jul
8 Aug

Figure 4_revised .

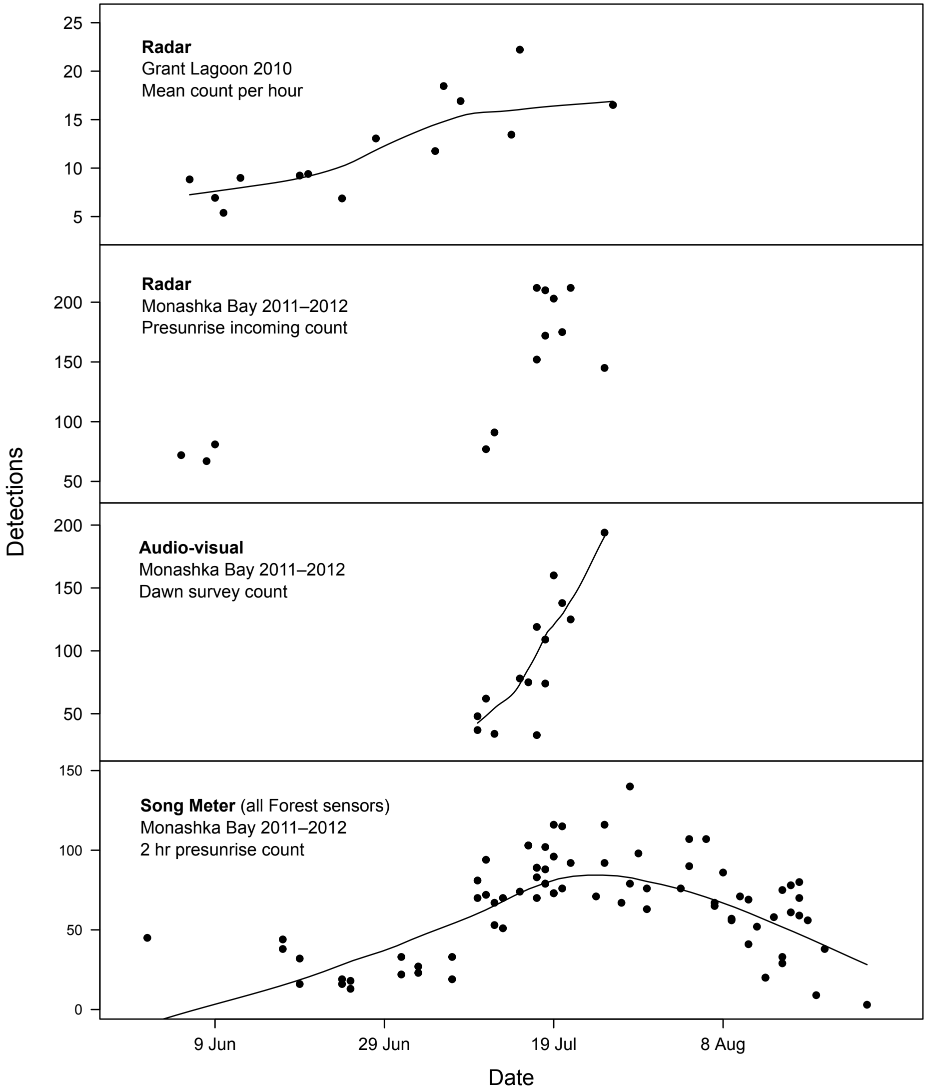
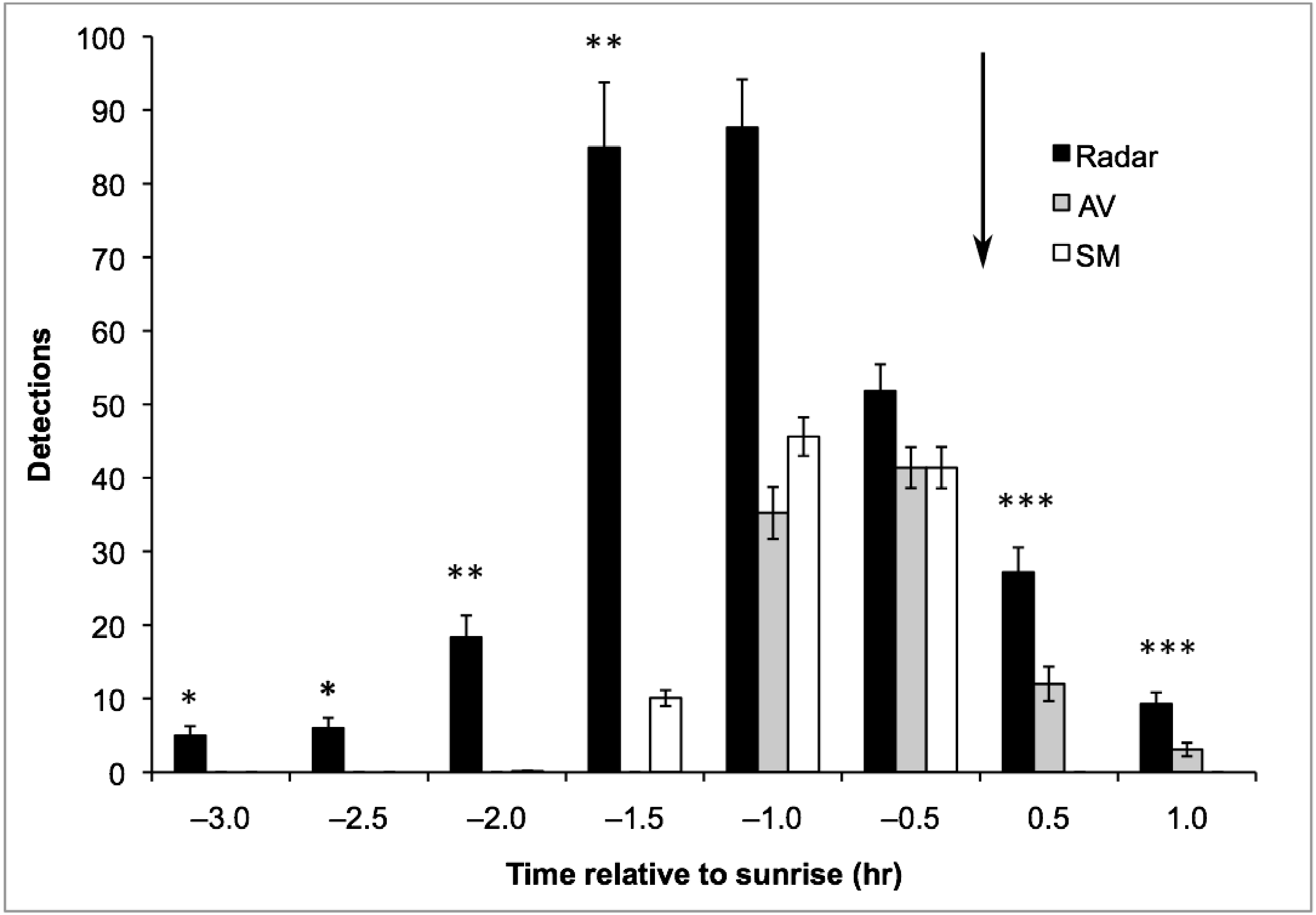

Radar
Grant Lagoon 2010
Mean count per hour
Radar
Monashka Bay 2011–2012
Presunrise incoming count
Audio-visual
Monashka Bay 2011–2012
Dawn survey count
Song Meter (all Forest sensors)
Monashka Bay 2011–2012
2 hr presunrise count
Detections
Date
9 Jun
29 Jun
19 Jul
8 Aug
25
20
15
10
5
200
150
100
50
200
150
100
50
150
100
50
0

Figure 4_revised .



100
90
80
70
60
50
40
30
20
10
0
Detections
Radar
AV
SM
*
*
**
**
***
***
–3.0
–2.5
–2.0
–1.5
–1.0
–0.5
0.5
1.0
Time relative to sunrise (hr)

Figure3_revised .

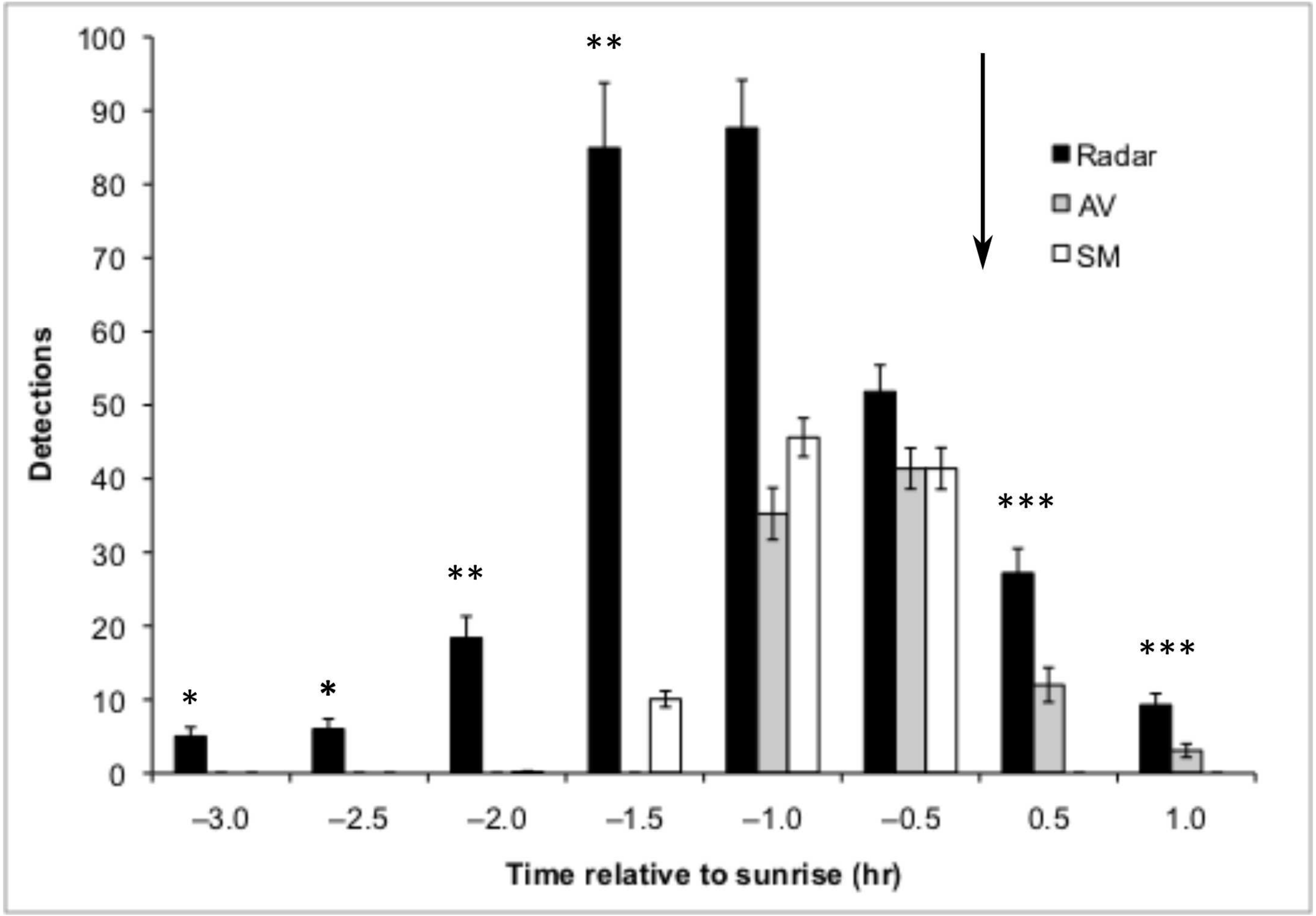


Figure3_revised .