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AT-SEA DENSITY MONITORING OF MARBLED MURRELETS IN CENTRAL CALIFORNIA: METHODOLOGICAL CONSIDERATIONS[1]

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Abstract. We conducted at-sea line transect surveys for Marbled Murrelets (*Brachyramphus marmoratus*) to determine density off the coast of central California and to explore the utility of various survey protocols. Surveys were designed to compare line versus strip transect methods, and reveal the effects of distance from shore, viewing conditions and seasonal trends on density estimates. On consecutive days, we conducted 12 paired (24 total) at-sea line and strip transect surveys that were 20 km long at 400 m and 800 m from shore. We also performed nine surveys that were 10 km long and at distances of 400 m, 900 m, 1,400 m, 2,400 m, 3,400 m and 4,400 m from shore. Density estimates calculated using line transects were significantly greater than estimates based on strip transects of 100 m and 200 m widths. Marbled Murrelet density ranged from 2.4–39.4 birds km^{-2} at 400 m from shore, and from 0.0–16.5 birds km^{-2} at 800 m from shore. Density was higher on the 400 m than on the 800 m survey on 22 of 24 survey days. Densities measured on consecutive days were highly correlated on the 400 m transect but not on the 800 m transect. Line transect densities on the 400 m transect were higher when conducted under better viewing conditions. Line transects had higher statistical power to detect trends than strip transects. Statistical power analyses indicated only a 24% chance of detecting a population declining by 5% per year over 5 years when surveying line transects 20 km in length five times a year. Power to detect a 5% annual change increased to 57% when surveying line transects five times per year over 10 years. Survey design should strive to minimize variability in bird density in order to maximize likelihood of detecting population trends. An increase in the number of surveys per breeding season, length of a transect, or duration of monitoring effort should increase power to detect trends in murrelet density. We suggest that at-sea surveys should focus on detecting trends in density rather than population size.

Key words: Marbled Murrelet, distance sampling methods, line transect, statistical power, at-sea surveys, Brachyramphus marmoratus.

INTRODUCTION

The breeding range of the Marbled Murrelet (*Brachyramphus marmoratus*) extends from central California to the Bering Sea (Carter and Morrison 1992, Ralph et al. 1995). It is unique among alcids by nesting in old-growth forests up to 100 km inland from the coast (Hamer 1995). Marbled Murrelet populations have been estimated to be declining at a rate of 4% to 6% annually in the Pacific Northwest (Ralph 1994, Beissinger 1995), and populations in Alaska and British Columbia may have declined by as much as 50% during the last 20 years (Kelson et al. 1995, Piatt and Naslund 1995). Productivity, as estimated by the ratio of juveniles to after-hatch-year birds, appears to be too low to sustain the population (Beissinger 1995), especially in the Pacific Northwest. Principal threats to the Marbled Murrelet are loss of nesting habitat to logging, mortality of birds at sea from oil spills, and gill-net fishing (Carter and Morrison 1992, Carter and Kuletz 1995). Because this threatened species uses commercially valuable old-growth forests for nesting, accurate population monitoring is necessary to make informed management decisions.

Monitoring Marbled Murrelet populations on land is difficult due to their scattered distribution in coastal forests and their secretive habits. Murrelets nest high in old-growth coniferous trees and nests are rarely seen, even on intensive surveys (Nelson and Hamer 1995). Auditory and

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visual detections of flying birds are the primary types of observations in forests, making it difficult to determine numbers of birds using a particular area. Population monitoring may best be done at sea, where individual birds can be surveyed. During the breeding season, the majority of murrelets occur in a narrow band along the coast near nesting areas (Carter and Morrison 1992, Ralph et al. 1995).

Despite recent improvements in murrelet surveys at sea, significant difficulties remain before these surveys can be used to determine accurate estimates of population size or trends. Current at-sea population monitoring techniques generally consist of strip transects, usually 100–200 m wide, with little replication (Ralph et al. 1995, Strong et al. 1995). Strip transects depend for their validity on detecting all birds within the strip, an assumption that is often violated (Buckland et al. 1993). Line transect sampling methods that incorporate the likelihood of sighting individuals at different distances from the transect line have been developed to minimize this bias (Buckland et al. 1993, Laake et al. 1994). At-sea surveys of Marbled Murrelets also assume that birds are distributed primarily as a function of distance from shore (Ralph et al. 1995, Strong et al. 1995). However, the relationship between murrelet density and distance from shore may vary between locations (Ralph et al. 1995, Strong et al. 1995), and such surveys have not been repeated frequently. To estimate population size for a region, samples usually are stratified by distance from shore, and density is calculated for each strata and then combined (Ralph and Miller 1995, Strong et al. 1995). It is especially problematic when offshore distribution patterns and density only are sampled in a limited area, and this distribution is then extrapolated over the entire species' range. The result is often a single estimate of population size with large confidence intervals due to extensive extrapolation from these few sampled areas (Ralph and Miller 1995, Strong 1995, Strong et al. 1995). These large confidence intervals make it very difficult to detect a moderate change in population size over time. Density estimates of marine mammals and seabirds from at-sea surveys also can be affected by viewing conditions (Buckland et al. 1993, Ralph and Miller 1995). Thus, information that can increase the precision, accuracy and statistical power of at-sea surveys to estimate population size and detect population trends is needed.

We systematically surveyed the main aggregations of a small, isolated population of Marbled Murrelets along the coast of central California from June to August 1995. Our sampling design was developed to compare survey methods and examine the factors affecting variation in population density estimates. The objectives of this study were to (1) compare distance sampling (line transect) methods to strip transects for estimating murrelet density, and estimate the variability of line transect density estimates by using consecutive days surveys, (2) examine how distance from shore, viewing conditions, and time within the breeding season affected murrelet density, and (3) determine the statistical power of survey designs to detect murrelet population trends.

METHODS

STUDY AREA

The at-sea population of Marbled Murrelets in central California is centered in the Año Nuevo Bay region (San Mateo and Santa Cruz Counties) and currently extends from Half Moon Bay to Aptos during the breeding season (Fig. 1) (Strong and Becker 1996). This population is the southernmost in the range of the species and is separated from the population in northern California by 240–320 km (Sowls et al. 1980, Carter and Erickson 1988, 1992). Its isolation decreases the likelihood that large numbers of birds would move into the study area from distant populations during the course of the study. It also is the smallest murrelet population, thought to number between 750 and 1,400 birds (Ralph and Miller 1995, Strong and Becker 1996). Old-growth forest nesting habitat for the central California population occurs only in areas adjacent to the Año Nuevo Bay region in Big Basin Redwoods State Park, Butano State Park and Portola Redwoods State Park, with smaller amounts in surrounding areas (Fig. 1). Several nests, eggshells, downy young, and fledglings have been documented throughout this area (Binford et al. 1975, Carter and Sealy 1987, Singer et al. 1991, 1995).

This discrete population of murrelets appears to have well-defined foraging sites on Año Nuevo Bay and near Pigeon Point where aggregations are found every year (Carter and Erickson

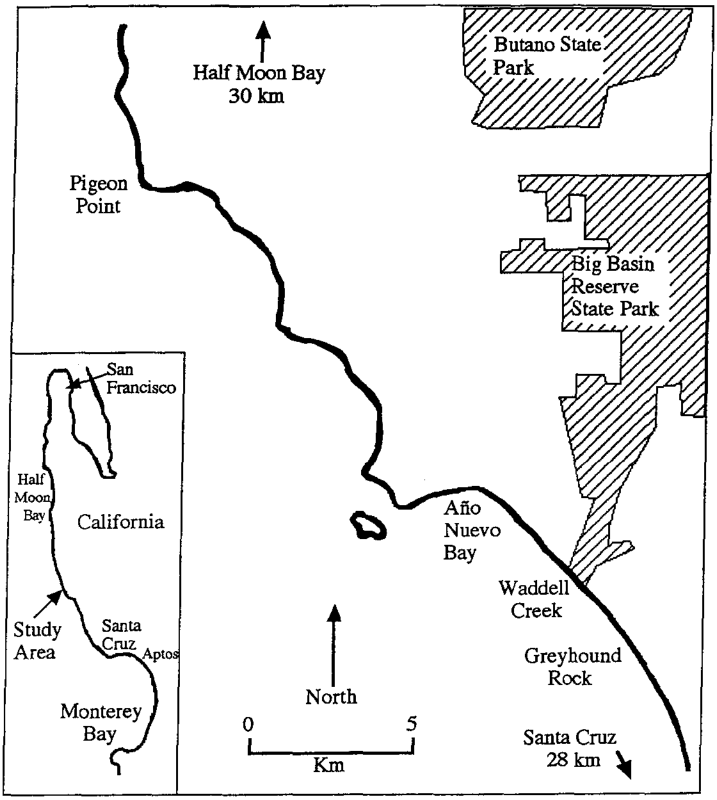

FIGURE 1. Location of at-sea survey area in central California indicating major coastal features and nesting areas. See text for survey routes.

1988, Strachan et al. 1995). Although some birds are found both north and south of the study area, regular observations and more detailed surveys have consistently found large numbers from Año Nuevo to Pigeon Point (Strong and Becker 1996). We chose this area for conducting our study to guarantee a relatively high number of sightings for population monitoring and assessing methodology.

SURVEYS

From 9 June to 20 August 1995, we conducted at-sea surveys of Marbled Murrelets from Greyhound Rock in northern Santa Cruz County to Pigeon Point in southern San Mateo County, which we refer to as the "Año Nuevo Bay region" (Fig. 1). We used a 4.3 m inflatable Zodiac with a 25 hp engine to travel along transect lines at approximately 18 km hr^{-1} (10 knots) at fixed distances from shore. We navigated using a Magellan 5000DLX hand-held Global Positioning System (GPS), and geodetic points that were obtained from 7.5 minute USGS topographic maps. All surveys were broken into segments that paralleled the shoreline at specified distances but allowed for curvature of the shoreline. Surveys were repeated with the use of the GPS and should be accurate to within several meters. The boat had one driver and two observers, one surveying one side of the vessel by scanning in a 90° arc from the beam to the bow of the boat. All personnel sat on the boat's pontoons during surveys, which resulted in an eye level of about 1.5 m above the water surface. Binoculars were used only to verify sightings. The vessel was slowed or stopped to make observations, and data were recorded with microcassette recorders. At the beginning of each survey, we towed buoys behind the boat at 25 m, 50 m, 75 m, and 100 m to aid in distance estimations.

For each sighting, we recorded time of day, number of Marbled Murrelets in the group, distance from the boat, angle from the transect line, and exact latitude and longitude. A group was defined as birds occurring within 2 m of one another (Strong et al. 1995), or birds sighted slightly farther apart that vocalized with one another, foraged together, or exhibited other behavioral cues that they were a group. The site of detection for groups was considered to be the weighted mean of the distances between birds. The location of birds, distance from the boat, and angle from the bow were recorded when the birds were first sighted to prevent overestimating density if birds avoided the vessel and moved away from the transect line (Buckland et al. 1993). The angle of birds off the bow was measured with angle boards accurate to 5°. Angle boards are similar to large protractors and facilitate quick estimation of angles. Flying birds were recorded only if they crossed the beam of the boat (e.g., 90° from the bow) and the distance was recorded at that point (Buckland et al. 1993). Locations of murrelets that flew into the area and landed were recorded. Distance from the transect line (D) was later calculated by the function $D = (d)(\cos \theta)$, where d is distance from the boat, and θ is the angle from the bow of the boat.

Two types of line transect surveys (also known as variable distance or variable width surveys) were conducted during the study. The first type, intensive surveys, recorded the distribution and density of birds in relation to distance from shore. Intensive surveys were conducted in Año Nuevo Bay from Greyhound Rock to 1 km North of Año Nuevo Island (Fig. 1) and were composed of transects 10 km in length that were oriented parallel to shore at distances of 400 m, 900 m, 1,400 m, 2,400 m, 3,400 m, and 4,400 m. This survey type was done nine times between 27 June and 7 August, 1995. The second type, extensive survey, recorded density in the Año Nuevo Bay region from Greyhound Rock to Pigeon Point (Fig. 1) and consisted of two 20 km transects at 400 m and 800 m from shore. The 400 m transect was done first, traveling north from the boat launch site on the beach just south of Waddell Creek. The 800 m transect was completed on the return trip. Extensive surveys were run in pairs on consecutive days to examine day-to-day variability in density and distribution, as well as population trends over the season. These transects were comprised of plots, each about 2 km long, to assist in maintaining the specified distance from shore. Twenty-four extensive surveys were conducted between 9 June and 20 August 1995.

Both extensive and intensive surveys began shortly after sunrise, usually from about 06:00 to 09:00. Viewing conditions were classified as excellent, very good, good, fair, and poor (after Strong et al. 1995) which corresponded to Beaufort sea states 0–4, respectively. Beaufort sea state 0 indicates completely calm seas, whereas a state of 4 indicates 25–35 cm wavelets, some white caps and winds over 10 knots. Conditions were downgraded one category if there was an unusually large swell. Surveys were not initiated under fair or poor conditions, or if the conditions were anticipated to deteriorate rapidly. Surveys were abandoned under poor conditions. The majority (91%) of surveys were conducted under excellent, very good or good conditions.

DATA ANALYSIS

Marbled Murrelet density was estimated using the computer program DISTANCE for line transect analysis (Laake et al. 1994). Line transect sampling assumes a 100% probability of detecting birds on the line, and that probability of detection decays with distance from the line. Distances from the line for all observations were examined in a histogram using 20 m interval classes to calculate the decay rate (Fig. 2). Detections over 160 m from the line were truncated to allow better model fit (Buckland et al. 1993, Laake et al. 1994). Detections were calculated as clusters of birds, and density was estimated using mean cluster size. The DISTANCE program models this decay rate with a polynomial function, determines the function that best fits the data, and uses it to calculate density.

The most consistent model selected by the DISTANCE program to simulate this diminution of the detection rate was a half-normal curve with a polynomial function and cosine adjustments. This model was selected for all extensive survey days pooled, and for 13 out of 24 individual days. The selection criteria for the model were based on the lowest value for Akaike's Information Criterion (AIC) (Akaike 1973). AIC selects a model as more informative when additional adjustment terms do not significantly increase the power of the model, thus keeping the model from becoming too complex. Models with the lowest AIC were selected as having the best fit (Buckland et al. 1993). When other models were selected by the DISTANCE program, they would sometimes give exceedingly high density estimates, due to insufficient data for fitting the model. All subsequent calculations used the half-normal curve with cosine adjustments to estimate the detection rate for Marbled Murrelets. The DISTANCE program also calculates effective strip width (ESW), coefficients of variation and average group size for each survey. ESW is the width of a strip transect with 100% detection that would yield a density equal to that of a line transect (Buckland et al. 1993). ESW is reported as half widths, so a 50 m ESW would require a 100 m wide strip-transect with 100% detection to achieve the density reported by a line transect. Density also was calculated using strip transects 100 m and 200 m wide (50 m or 100 m on either side of the boat, respectively) and 20 km long for extensive transects. The total area covered was divided by the total number of birds sighted within the designated strip width to obtain a density (birds km^{-2}) for the strip transects. Densities on the intensive transects (each 10 km in length) were calculated only using line transect analysis. All densities are reported as means ± SE.

Statistical analyses were done using SYSTAT (1994). We used Pearson's correlation coefficients to examine relationships between murrelet densities on consecutive days. The distributions of density values within different classes of viewing conditions and within line and strip transect density estimates were not normally distributed, as determined by inspecting histograms. Thus, nonparametric tests were used for these comparisons. Paired Wilcoxon's matched-pairs signed ranks tests were used to test for differences in density estimates among line transects, 100 m and 200 m strip-transects. Mann-Whitney U-tests were used to examine differences in density estimates between viewing conditions. We pooled excellent with very good days, and good with fair days for this analysis.

We calculated the statistical power of our surveys to detect changes in population size from year to year using the software MONITOR (Gibbs 1995). Population trends are detected by regressing population density estimates against time (Thomas and Martin 1996) and using a one-tailed t-test to determine if the slope of the line is significantly different from zero (Gibbs 1995). Scenarios which included the ability to detect trends under various sampling regimes and time durations were explored. Only data from the 400 m transect were used because test simulations showed that the low density and higher standard error on the 800 m transects dramatically decreased power to detect trends.

We examined the probability of detecting population trends ranging from −10% to +10% per year over five years of annual surveys with 5 survey replicates per year of 20 km in length. These simulations compared the relative power of line transects, and 100 m and 200 m wide strip transects. Scenarios were selected because those distances and survey frequencies may be repeated easily during the breeding season. A second set of simulations was conducted comparing the power of line transects over 10 years of surveys replicated three, five, or ten times per year. Alpha levels (type I error rate) were set to 0.10 for all simulations. One-tailed t-tests were used to test the null hypothesis that trends have no detectable difference from zero. All simulations included 1,000 iterations. Analyses used the mean and standard deviation of density calculated by DISTANCE from the extensive surveys. Mean densities and standard deviation for statistical power projections of strip transects were obtained by dividing the number of murrelets sighted within a strip by the area covered. Power to detect a negative trend is particularly important, because murrelet populations are thought to be declining 4–6% per year (Beissinger 1995).

RESULTS

DISTANCE SAMPLING VERSUS STRIP TRANSECT METHODS

Marbled Murrelets were detected at a higher rate closer to, than farther from, the transect line (Fig. 2). High levels of detection extended to 40 m and dropped thereafter. This resulted in a nearly level shoulder in the histogram from 0–40 m that is required by the DISTANCE program to calculate density accurately and to correct for the decay in detectability (Buckland et al. 1993). The presence of a shoulder indicates that we met our goal of detecting and recording birds before they were disturbed by our vessel. Although actively foraging murrelets may dive out of view for 17–44 sec, with a maximum of 115 sec (Thorenson 1989, Carter and Sealy 1990, Strachan et al. 1995), our slow rate of speed and attention to the area well in front of the boat should have minimized the number of birds missed while diving.

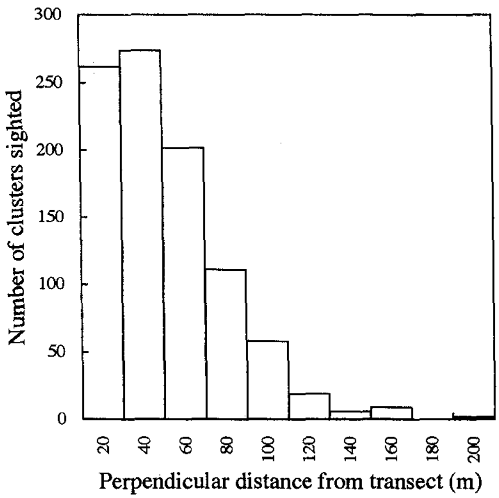

FIGURE 2. Histogram displaying the distance from the transect line that one or more Marbled Murrelets (clusters) were sighted during the study (n = 960).

Murrelet densities on extensive transects varied from 2.4–39.4 birds km^{-2} at 400 m from shore and averaged 15.8 ± 1.8 birds km^{-2}. At 800 m from shore, densities ranged from 0.0–16.5 birds km^{-2} with an average of 5.6 ± 0.9 birds km^{-2}. Murrelet density estimates calculated using the line transect method were significantly greater than estimates based on strip-transects with widths of 100 m or 200 m at both 400 and 800 m from shore (Table 1). On the 400 m transect, 100 m and 200 m wide strip transects resulted in an average of 13.7 ± 1.6 and 9.7 ± 1.4 birds km^{-2}, respectively. On the 800 m transect, 100 m and 200 m wide strip-transects resulted in an average of 4.3 ± 0.8 and 2.7 ± 0.5 birds km^{-2}, respectively. Differences in murrelet density between survey methods were smaller at 800 m than at 400 m from shore because the density of birds was much lower farther from shore.

Consistency of line-transect density estimates was high, as evidenced by a high correlation between densities on consecutive days at 400 m (r^2 = 0.50, P = 0.01; Fig. 3A). At 800 m, a positive but insignificant correlation was found (r^2 = 0.01, P = 0.25; Fig. 3B), probably due in part to the high variability between days and low density of murrelets at this distance from shore. High repeatability of density measurements also was found for 100 m wide strip transects at 400 m (r^2 = 0.48, P = 0.02) but not at 800 m (r^2 = 0.02, P = 0.95).

FACTORS AFFECTING MURRELET DENSITY ESTIMATES

Marbled Murrelet densities were significantly greater at 400 m than at 800 m from shore (Z = 3.95, df = 22, $P < 0.001$). More birds were sighted on the 400 m transect than on the 800 m transect on 22 of 24 days. Intensive surveys also found the greatest density of Marbled Murrelets at 400 m from shore (Fig. 4). Density declined rapidly to 1,400 m. No murrelets were detected beyond 1,400 m during the entire study, and few birds were detected on the 1,400 m transect (Fig. 4).

The proportion of murrelets detected at different distances from shore varied among days but clear trends emerged (Table 2). An average of 83% of the Marbled Murrelets were detected on the 400 m transect, 14% were observed on the 900 m transect, and 3% were encountered on the 1,400 m transect. From 85–100% of the murrelets were sighted on the 400 m transect on seven of nine days. On the other two days (8 and 20 July), however, the proportion of birds detected was slightly higher at 900 m than at 400 m from shore.

TABLE 1. Results of paired Wilcoxon signed ranked tests between line transects, 100 m and 200 m strip transects on 400 m and 800 m extensive transects.

Distance from shore	Comparison	Mean difference between estimates	Z	df	$P \leq$
400 m	line vs. 100 m strip	2.11	3.657	23	0.001
	100 m vs. 200 m strips	3.75	4.037	24	0.001
	line vs. 200 m strip	6.17	4.286	23	0.001
800 m	line vs. 100 m strip	1.21	3.397	19	0.001
	100 m vs. 200 m strips	1.59	3.789	18	0.001
	line vs. 200 m strip	13.19	3.920	19	0.001

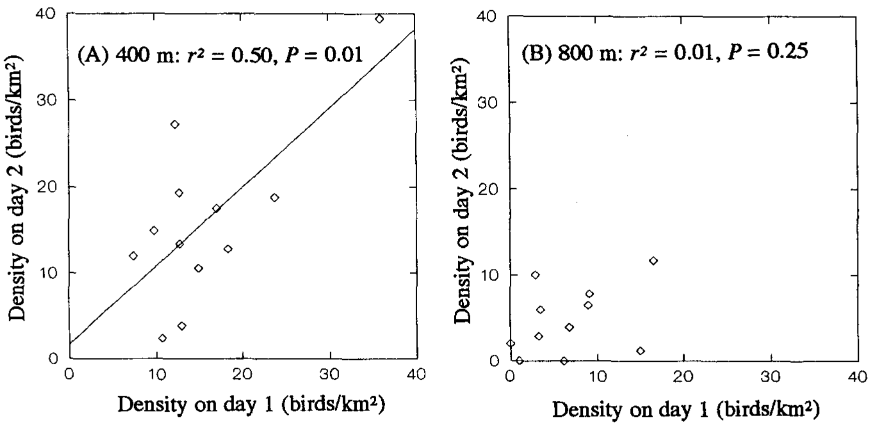

FIGURE 3. Relationship between Marbled Murrelet densities estimated by the line transect method on paired survey days at 400 m (A) and 800 m (B) from shore.

Line transect densities were affected by viewing conditions on the 400 m transect (Fig. 5A). The number of birds sighted (U = 136.5, n_1 = 10, n_2 = 15, P = 0.001) and the calculated density (U = 113.0, n_1 = 10, n_2 = 14, P = 0.01) were greater on the 400 m transect on days with excellent or very good viewing conditions compared to days with good or fair conditions. Effective strip width (ESW) also was significantly greater (U = 114.0, n_1 = 10, n_2 = 14, P = 0.01) on the superior viewing days. Surveys with excellent or very good viewing conditions had an ESW of 66 ± 4 m, whereas the ESW for the good or fair days was 49 ± 3 m. On the 800 m transect (Fig. 5B), no significant differences related to viewing conditions were detected for density (U = 63.0, n_1 = 6, n_2 = 18, P = 0.55), number of murrelets sighted (U = 75.5, n_1 = 6, n_2 = 18, P = 0.15) or ESW (U = 78.0, n_1 = 6, n_2 = 17, P = 0.06).

Marbled Murrelet density at sea varied during the course of the breeding season (Fig. 6), and showed some evidence of seasonal trends at 400 m from shore. Density rose from about 5–10 birds km^{-2} in June to 20–30 birds km^{-2} in July. Density peaked around 19 July at 400 m and had nearly returned to early June densities (circa 9 June) by early August (circa 31 July). Density at 800 m remained relatively constant until late July, when a slight decline was evident.

POWER ANALYSES

Power analyses revealed that when comparing 20 km line, and 100 m and 200 m strip transects, statistical power was highest for line transects (Fig. 7A). However, power was still low when using line transects. Line transects surveyed five times per year resulted in power of only 0.24 to detect a negative population change of 5% per year over 5 years. A power of 1.00 indicates a 100% chance of detecting a trend in the population at any given alpha value. Power of line transects more than doubled when surveys were simulated for ten years (Fig. 7B). However, surveys replicated five times per year over ten years still had only a 57% chance of detecting a 5% annual population decline. Over 5 years, an annual decline of 5% and 10% per year compounds to a total decline of 18.5% and 34.4%, respectively, in population density.

DISCUSSION

Systematic surveys can tease apart sources of variability and determine ways to maximize sampling effectiveness and efficiency. Whereas there is a large body of theory on at-sea sampling (Buckland et al. 1993), at-sea survey methods for the Marbled Murrelet must be designed to incorporate the unique ecology of this species and the problems that these attributes create for population monitoring efforts.

The Marbled Murrelet population in the Año Nuevo Bay region was moderately dense compared to other regions. An average of 13.7 ± 1.6 birds km^{-2} was recorded on 100 m wide strip transects at 400 m from shore, which we report here to facilitate comparison with studies using this methodology elsewhere. In other areas, murrelet densities from strip counts ranged from about 5 birds km^{-2} in Washington and northern

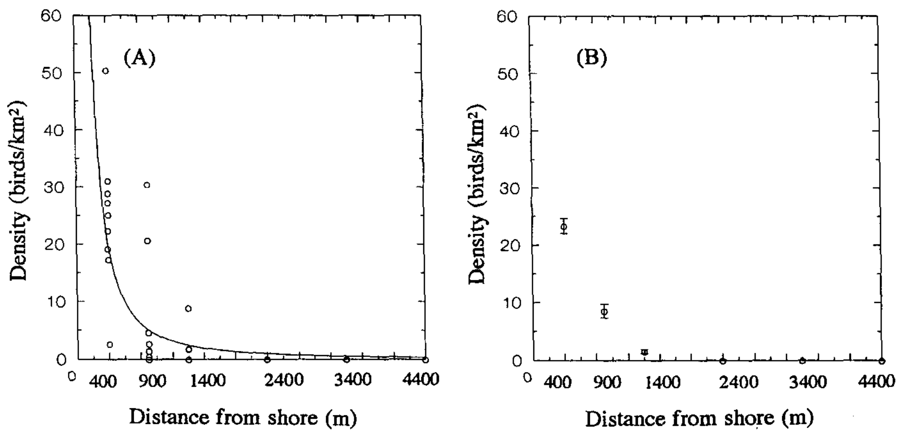

FIGURE 4. (A) Density of murrelets on intensive transects as a function of distance from shore. (B) Average and standard error of murrelet density for intensive transects using the line transect method.

California (Ralph and Miller 1995, Speitch and Wahl 1995) to as high as 20–100 birds km^{-2} in some areas of Alaska (Piatt and Naslund 1995) and Oregon (Varoujean and Williams 1995). Because murrelet density in the Año Nuevo Bay region was intermediate compared to other areas, many of our conclusions concerning murrelet detection, survey design, data analysis and statistical power should be useful for other sites and survey programs.

CHOICE OF SAMPLING METHODS

Line transects are more accurate than strip transects in estimating density because strip transects miss birds and underestimate actual density (Buckland et al. 1993). Additionally, strip transects only report an index of population density, whereas line transects calculate an estimate of density. Indices are precarious because they cannot be rigorously examined for validity. In this study, strip transects produced average lower densities than line transects, and this difference was significant. Line transects calculate the number of birds missed by modeling the decay in detections with distance from the transect line, but strip transects do not account for the inevitable missing of birds. Mean murrelet density at 400 m was 15.8 birds km^{-2} on the line transect, 13.7 birds km^{-2} on the 100 m strip transect and 9.7 birds km^{-2} on the 200 m strip transect. This is a ratio of 100:87:61 for the line, 100 m strip, and 200 m strip, respectively, indicating that even using what has been thought of as a conservative strip width of 100 m can underestimate density. For example, the current estimate of the total Marbled Murrelet population in the Pacific Northwest (Washington, Oregon and California) is 18,550 birds, calculated primarily using strip transects of 100 m or more in width (Ralph and Miller 1995, Ralph et al. 1995, Varoujean and Williams 1995). Other methodological considerations aside, our data suggest that using line transects would have estimated a population size of 21,382 birds. Here the bias is not extreme, as would result from estimates based on 200 m strip transects. The decline in detection rate at 40 m from the boat (Fig. 2) indicates that birds will be missed when conducting strip transects more than 80 m wide. Our findings contrast with Ralph and Miller's (1995) conclusion that a strip transect width of

TABLE 2. The proportion of Marbled Murrelets detected at different distances from shore in Año Nuevo Bay, California, in 1995.

	Distance from shore (m)					
Date	400	900	1,400	2,400	3,400	4,400
27 June	1.00	0.00	0.00	0.00	0.00	—
8 July	0.48	0.52	—	—	—	—
15 July	0.86	0.14	0.00	0.00	0.00	0.00
20 July	0.39	0.47	0.14	0.00	0.00	0.00
21 July	0.92	0.02	0.06	0.00	0.00	0.00
26 July	1.00	0.00	0.00	0.00	0.00	—
30 July	0.87	0.08	0.05	0.00	0.00	0.00
2 August	1.00	0.00	0.00	0.00	0.00	0.00
6 August	0.94	0.06	0.00	0.00	0.00	—
Mean	0.83	0.14	0.03	0.00	0.00	0.00
SD	0.23	0.21	0.05	0.00	0.00	0.00

— No data collected.

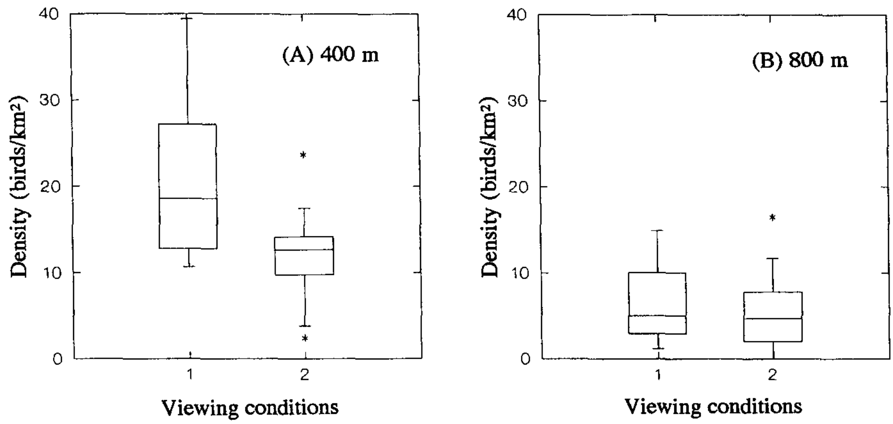

FIGURE 5. Boxplots of Marbled Murrelet density estimated by the line transect method at 400 m (A) and 800 m (B) from shore as a function of viewing conditions: 1 represents excellent and very good viewing conditions, and 2 represents good and fair viewing conditions. Sightings made under poor conditions were excluded. The line inside the box represents the median value. The 25th and 75th percentiles are shown by the bottom and top of the box, respectively. Whiskers represent 1.5 times the interquartile range between the absolute values of the top and bottom of the box. Asterisks are outliers (SYSTAT 1994).

200 m in Beaufort states up to 3 did not miss a significant number of birds. However, they used boats with a slightly higher and more stable observer platform, which may have permitted detection at farther distances.

It is essential that line transect surveys achieve a detection rate of 100% near the transect line to ensure accurate modeling of the decay in detection rate with increasing distance from the transect line (Buckland et al. 1993). Marbled Murrelets can be disturbed by the oncoming boat and it is imperative that the position of a bird be recorded before it begins to swim away from the vessel. Line transect surveys that count birds once they come abeam of the boat, by which time they have probably moved some distance away from the transect line, do not meet this requirement and will give inaccurate estimates. We successfully avoided this problem by attempting to record the positions of clusters of murrelets when they were first seen, usually at least 30 m in front of the boat, and using angle boards to assist in estimating distance from the transect line. The presence of a nearly flat shoulder in detection rate near the boat (Fig. 2), indicated that murrelets typically had not begun to flee the boat before detection.

Marbled Murrelet density on back-to-back days was significantly correlated at 400 m from shore, suggesting that transect counts had good repeatability and that changes in density were small over very short time periods. No significant correlation between densities on consecutive days occurred on the 800 m transect probably due to low likelihood of encountering birds there. We recommend concentrating efforts for detecting population trends in areas of higher known density and surveying low density areas farther from shore less often, primarily to determine changes in distribution.

INCORPORATING OR PRECLUDING FACTORS AFFECTING DENSITY ESTIMATES

Densities of murrelets were higher closer to than farther from shore (Fig. 4). This result also was reported for coastal waters of Oregon (Strong 1995, Strong et al. 1995, Varoujean and Williams 1995) and in the bays of British Columbia (Kelson et al. 1995), but not in northern California waters (Ralph and Miller 1995). Marbled Murrelets, like other alcids, are constrained by the depth to which they can dive and by the distribution of their prey. Both of these variables are related to distance from shore. Although the majority of birds were sighted on the 400 m transect, there was day-to-day variation in the distribution of birds from shore (Table 1). This complicates estimation of total population size using weighted averages (Strong et al. 1995, Strong and Becker 1996) or linear regression (Ralph and Miller 1995) to infer offshore densities.

Viewing conditions during our surveys had a significant effect on murrelet density estimates,

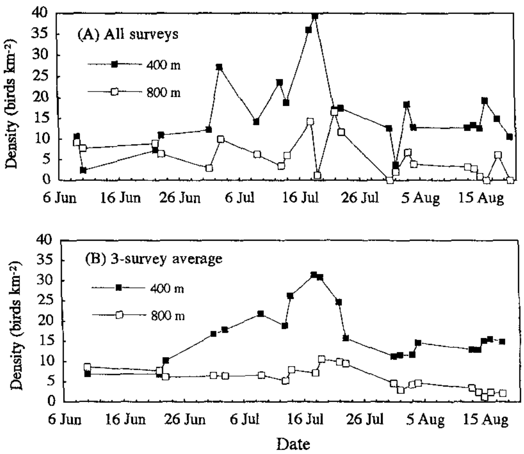

FIGURE 6. Estimated densities for Marbled Murrelets at 400 m and 800 m from shore using the line transect method for each day (A) and for a running average of three survey dates (B).

suggesting that even line transects are not immune to such biases (Fig. 5). Densities were significantly lower on the 400 m transect under good and fair viewing conditions (Beaufort states 2 and 3) than during excellent and very good sea states (Beaufort states 0 and 1). Surveys conducted under these less than adequate conditions produced lower density estimates because some birds were probably not detected, although Ralph and Miller (1995) found no decrease in murrelet detections until the sea state reached Beaufort state 3. As no method to account for bias due to different viewing conditions has been developed, we suggest that surveys be avoided in anything less than excellent or very good viewing conditions (Beaufort states 0 and 1).

Density remained fairly constant over the summer on the 800 m transect, but showed an apparent short-lived peak on 18 and 19 July on the 400 m transect (Fig. 5). Whether this represents a regular seasonal trend or was simply a result of temporary movements remains to be determined. Population changes could occur during the course of the breeding season as nesting birds will spend more time away from the ocean incubating or feeding young. Murrelets could move into or out of an area, although this seems less likely in our population because of its isolation. Detecting population trends will require conducting regular surveys within a period when murrelets do not appear to be immigrating or emigrating.

Other factors that also could affect population estimates should be considered in designing monitoring programs. All of our surveys except one were performed at nearly the same time in the morning, minimizing any bias in density that might be due to time of day. Water temperature

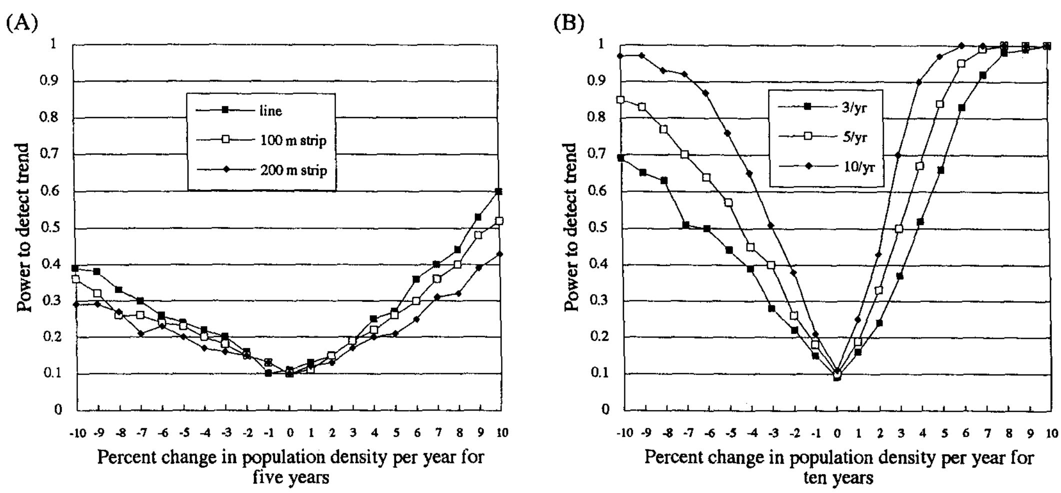

FIGURE 7. Statistical power to detect population trends for the Marbled Murrelet in central California (alpha = 0.10). (A) Results are shown for 20 km transects surveyed five times each year for five years using line transects, 100 m wide strip transects or 200 m wide strip transects. (B) Comparison of statistical power to detect trends over 10 years when repeating surveys 3, 5, or 10 times per year using the line transect method. A 10% annual decline over 5 years is equal to an overall decline of 34.4%.

was not recorded but could affect murrelet density by affecting prey distribution, since colder areas are usually due to nutrient rich, deep water upwelling (Pingree et al. 1978). Ainley et al. (1995) found that the water temperature in Año Nuevo Bay, which had the highest murrelet density in our study area, was slightly cooler than the surrounding areas due to an eddy and deep water upwelling.

STATISTICAL POWER AND DESIGNING EFFECTIVE SURVEYS

Knowledge of the statistical power of a survey program is essential if surveys are to detect changes in population size or density. Power to detect population trends is a function of the mean and variance in density, which are affected by the number of times surveys are repeated and by transect length. Negative trends are more difficult to detect (Fig. 7) and are our primary concern for this threatened species whose population has apparently declined dramatically in the past 20 years (Beissinger 1995, Kelson et al. 1995, Piatt and Naslund 1995). None of the at--sea survey programs for Marbled Murrelets have addressed statistical power to detect trends as an objective or concern of survey design. If power is low, then surveys are doing little more than recording presence or absence, and are unlikely to detect changes in population size or density.

Power analysis suggested that murrelet surveys consisting of relatively short transects (20 km) conducted five times per breeding season are not likely to detect a population trend over five years (Fig. 7A). Our analyses did not include inter-annual variation in density, which would likely further reduce power. Power may be increased by reducing variability through the use of line transects, lengthening surveys, and surveying in areas of relatively high density. Shorter transects may be advantageous because they preclude several factors that may affect densities, such as tides and time of day, but they will need to be conducted more often to retain statistical power. Shorter transects, however, may increase variability due to short term movements of birds into or out of the survey area. Longer transects may reduce some of this variability because they are not as sensitive to small scale movements. Preliminary data suggest that 100-km long surveys in the Año Nuevo Study area have a higher power to detect trends with fewer replicates per year than 20-km surveys due to a lower standard deviation in the density estimate (Becker and Beissinger, unpubl. data). Although it may be difficult to arrange surveys often enough or of the lengths necessary to ensure a high statistical power to detect trends, knowledge of the statistical power of the surveys being performed is needed to redirect sampling efforts that may be too infrequent or short to be useful.

CONCLUSIONS

In our opinion, current approaches for monitoring Marbled Murrelets at-sea need to be redesigned. The majority of Marbled Murrelet surveys at-sea (Piatt and Naslund 1995, Ralph and Miller 1995, Strong 1995, Strong et al. 1995) have had extensive geographic coverage, little replication, relied primarily on strip-transects and have not considered statistical power to detect trends. Often surveys have attempted to determine population size for an entire region by extrapolating densities from strip transects with little replication over much larger ocean areas. This has resulted in large confidence intervals around population and density estimates. For example, Strong et al. (1995) had 95% confidence intervals between 10,980 and 31,564 Marbled Murrelets in Oregon for 1992 using line transects. With this type of survey design, it becomes almost impossible to detect changes in a population's size over time with confidence. Under such sampling regimes, little can be said about whether the population numbers are indeed changing from year to year or over a period of several years.

We suggest that future at-sea monitoring efforts for murrelets shift from estimating population size for large geographic regions to detecting changes in population density within limited geographic areas. Trend analysis should be more powerful, accurate, and efficient than attempts to enumerate the entire population because more replications may be completed and there is little or no extrapolation involved. Statistical power to detect trends in murrelet populations may become satisfactory when transects are surveyed repeatedly using line transects, and can be improved by increasing the number of surveys per season or extending transect length. Our results also suggest that line transects should be used because they are more accurate than strip transects in estimating density and they yield a lower standard deviation. It is important that line transect surveys achieve a detection rate close to 100% near the transect line or estimates will be inaccurate due to incorrect modeling of the decay function. Surveys should be performed in Beaufort states 0 or 1, if possible, to avoid bias due to viewing conditions. Variation in densities of murrelets at different distances from shore also will need to be considered.

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