DISTRIBUTION, ABUNDANCE AND POPULATION TRENDS OF THE KITTLITZ'S MURRELET *BRACHYRAMPHUS BREVIROSTRIS* IN PRINCE WILLIAM SOUND, ALASKA

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SUMMARY

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Monitoring population trends of rare species can be difficult if they cannot be readily separated from closely related, abundant species. Such species identification problems affect monitoring in Prince William Sound (PWS), Alaska, where Kittlitz's Murrelets *Brachyramphus brevirostris* co-exist with Marbled Murrelets *B. marmoratus*. We examined murrelet trends using data from PWS-wide surveys conducted in 11 years between 1972 and 2007, and models that incorporated murrelets not identified to species in population estimates. We examined modeled trends with and without unusually high (1972, 1993) or low (1998) population estimates. In 2001 and 2009, we also conducted intensive surveys for Kittlitz's Murrelets. Based on field estimates, identified Kittlitz's Murrelets declined by 63% (5% per annum) between 1989 and 2004 but appeared stable thereafter. Model estimates that incorporated unidentified birds suggested a steeper decline of 13% per annum between 1989 and 2007, and negative trends were obtained regardless of which years were included. Marbled Murrelets showed a lower rate of decline in modeled estimates, but field estimates for identified Marbled Murrelets continued to decline after 2004. Intensive surveys for Kittlitz's Murrelets produced a higher population estimate in 2009 than in 2001. Recent estimates for Kittlitz's Murrelet were 2346 birds (95% CI 514–4178) from the PWS-wide surveys in 2007, and 2080 birds (1409–2990) from the intensive surveys in 2009. We conclude that both murrelet species have declined since 1972, with the lower population size and restricted distribution of the Kittlitz's Murrelet putting it at greater risk of extirpation in PWS. Kittlitz's Murrelet may have stabilized after the mid-2000s, but our sample size was insufficient to make a determination. Our results emphasize that future conservation efforts will depend on frequent, long-term monitoring of species-specific trends.

Key words: Kittlitz's Murrelet, *Brachyramphus brevirostris*, Marbled Murrelet, *Brachyramphus marmoratus*, Prince William Sound, Alaska, boat surveys, population declines

INTRODUCTION

Identifying and interpreting trends in populations is a critical aspect of conservation and management of fish and wildlife species. Among rare species, detection of trends is often difficult because of uncertainty in population estimates and short time-series of data (Taylor & Gerrodette 1993, Harwood & Stokes 2003). For closely related species that are difficult to distinguish, another source of uncertainty is species identification (Hey *et al*. 2003). Incomplete species-specific data can result in trends of rare species being masked by trends in the more abundant species, possibly leading to crypto-extinctions of the rare species (Ludwig *et al*. 1993, Roberts & Hawkins 1999, Dulvy *et al*. 2000). We faced these problems in attempts to determine the population status of the Kittlitz's Murrelet *Brachyramphus brevirostris*, which typically co-exists in Alaska with the relatively abundant Marbled Murrelet *B. marmoratus*. In Prince William Sound (PWS), Alaska, these phenotypically similar murrelets are sympatric, with the Kittlitz's Murrelet found almost exclusively in fjords with tidewater glaciers (Kendall & Agler 1998, Day *et al*. 2003, Kuletz *et al*. 2003) and the Marbled Murrelet found throughout nearshore waters of PWS. Marbled Murrelets outnumbered all other seabird species in summer until about 2000 (Agler *et al*. 1998), and remained one of the more abundant species between 2000 and 2007 (McKnight et al. 2008). Lance *et al*. (2001) reported that the combined population of *Brachyramphus* murrelets had declined in PWS since at least 1989, and probably since 1972. However, year-to-year variability in species identification reduced their confidence in interpretation of species-specific trends.

Most of the world's known populations of Kittlitz's and Marbled murrelets are found along Alaska's coastlines (Day *et al*. 1999, McShane *et al*. 2004), and PWS hosts relatively large populations of both species (Agler *et al*. 1998). PWS is one of the few regions in Alaska with long-term, at-sea survey data for marine birds, including *Brachyramphus* murrelets. PWS-wide surveys for all marine bird species were conducted in 11 years between 1972 and 2007 (Klosiewski & Laing 1994, Irons *et al*. 2000, Lance *et al*. 2001, McKnight *et al*. 2008). While that level of coverage is exceptional for marine birds in Alaska, the PWS-wide survey was not ideal for estimating trends of Kittlitz's Murrelet because of the species' clumped distribution and the difficulty of distinguishing it from the Marbled Murrelet in the field. Different proportions of murrelets were identified to species over the years (Kendall & Agler 1998). Therefore, to increase the precision of population estimates of this species in PWS, we conducted intensive surveys specifically for Kittlitz's Murrelet in selected habitats of PWS in 2001 and 2009.

In this paper we report the most current distribution, abundance and trend estimates of Kittlitz's and Marbled murrelets from 11 PWS-wide surveys conducted over 36 years (1972–2007). To address issues related to species identification and anomalous survey years, we constructed models that incorporated unidentified birds into population trend predictions and evaluated the inclusion and exclusion from the data set of three anomalous years. We present and compare empirical estimates derived from field data and model-generated estimates to assess the status of the Kittlitz's Murrelet in PWS. We also used two intensive surveys of habitats commonly used by Kittlitz's Murrelets to derive independent estimates of population size for comparison with the PWS-wide surveys.

STUDY AREA

PWS is a ~10 000 km^2 protected body of water in the northern Gulf of Alaska (GOA; Fig. 1). Its convoluted shoreline includes deep fjords, shallow bays, deltas and dozens of large and hundreds of small islands. There are several large icefields and more than 20 tidewater glaciers entering coastal waters (Molnia 2001). Bays, fjords and large islands without tidewater glaciers receive glacial runoff from land-locked glaciers. The high freshwater input from rain and snow or glacial melt drives strong circulation that generally runs east to west (Neibauer *et al*. 1994). Surface waters from the GOA pulse into PWS primarily during winter months, via the Alaska Coastal Current, while in summer PWS waters become warmer and stratified (Niebauer *et al*. 1994). Bays in PWS average <50 m deep, whereas fjords may be >400 m deep (Gay & Vaughan 1998). Compared to average PWS conditions, tidewater glacier fjords tend to have cooler, fresher waters, with stronger and shallower (10–15 m) vertical gradients in temperature (thermocline) and salinity (halocline) (Gay & Vaughan 1998). Tides are semidiurnal and range up to 6 m.

METHODS

PWS-wide surveys

Data collection

Between 1972 and 2007, we conducted PWS-wide surveys in 11 years (1972, 1989–91, 1993, 1996, 1998, 2000, 2004, 2005 and 2007) during July, which is mid-breeding season (chick-rearing) for

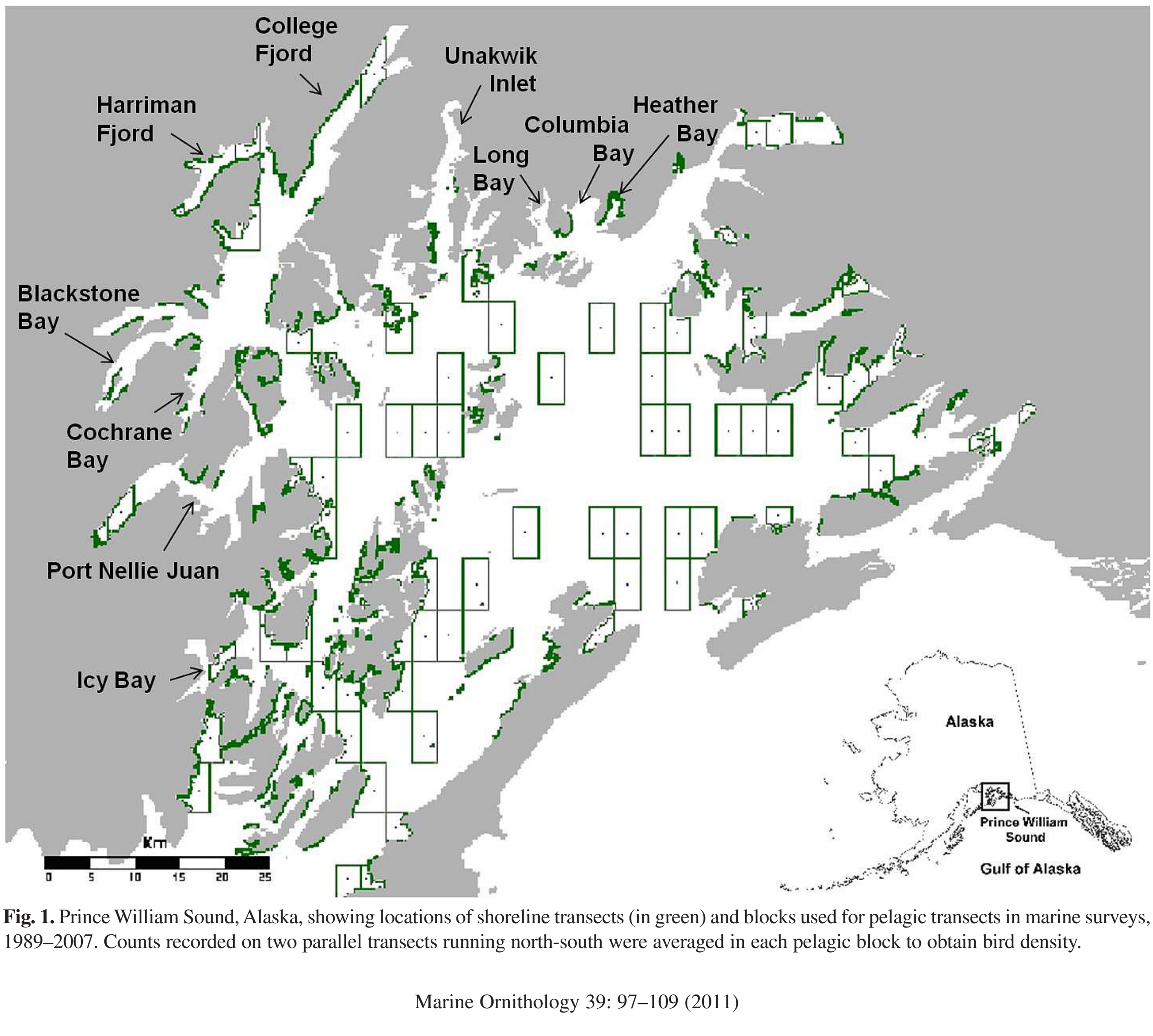

Fig. 1. Prince William Sound, Alaska, showing locations of shoreline transects (in green) and blocks used for pelagic transects in marine surveys, 1989–2007. Counts recorded on two parallel transects running north-south were averaged in each pelagic block to obtain bird density.

Kittlitz's Murrelets in PWS (Day *et al*. 1999, 2003). The surveys were designed to collect data on all marine birds. The 1972 survey design differed slightly from the rest, although in all years the vessel size and transect widths were similar, and the entire survey was completed in 2–3 weeks (Klosiewski & Laing 1994, Agler *et al*. 1998). Both designs also had two primary strata, shoreline and offshore. The shoreline stratum comprised waters ≤200 m from shore, and the offshore stratum comprised all remaining waters.

In 1972 the shoreline stratum also included some entire bays (those selected bays <400 m across) small enough for all birds to be counted (Klosiewski & Laing 1994), and shoreline transects were determined with a US Geological Survey map. Offshore transects were placed at 4.8 km intervals and oriented southeast to northwest at 315° (true north). It was then assumed that bird densities on each offshore transect were representative of the area 2.4 km to each side of the transect (Klosiewski & Laing 1994).

In the 1989–2007 study design, start and end points of 742 shoreline transects (≤200 m from and parallel to shore) were demarcated by prominent shoreline features, and 212 such transects were randomly selected from the total (Klosiewski & Laing 1994, Agler *et al*. 1998). The offshore stratum was post-stratified into coastal-pelagic and pelagic strata (Fig. 1). Coastal-pelagic transects were in blocks that intersected the shore, whereas pelagic transects were in blocks that did not touch shore. The coastal-pelagic and pelagic transects were randomly selected from blocks 9.3 km long and sampled with a two-stage cluster design (Klosiewski & Laing 1994); within each block, we surveyed two north-south transect lines (secondary lines) located one minute of longitude inside the eastern and western boundaries (Agler *et al*. 1998). In total, 325–350 transects were sampled per year. Crews on three 8 m boats traveling at 10–15 km/hr operated simultaneously to complete the survey in <3 weeks (details in Agler *et al*. 1998, Irons *et al*. 2000, Lance *et al*. 2001).

TABLE 1
Field population estimates for *Brachyramphus* murrelets in July in Prince William Sound, Alaska, during PWS-wide surveys, 1972–2007

Year	Estimate (SE)		
	Kittlitz's Murrelet	Marbled Murrelet	Unidentified murrelet[a]
1972	63 229 (40 879)	236 633 (26 391)	4570 (4018)
1989	6436 (1583)	59 284 (5939)	41 634 (4129)
1990	5231 (4250)	39 486 (5018)	36 624 (3975)
1991	1184 (563)	42 477 (4599)	62 816 (7042)
1993	2710 (675)	14 177 (2261)	142 546 (21 045)
1996	1280 (685)	63 455 (8062)	17 429 (3010)
1998	279 (96)	49 921 (4746)	3038 (1072)
2000	1033 (673)	52 278 (7271)	1046 (509)
2004	780 (260)	35 593 (3930)	836 (186)
2005	2689 (1548)	33 797 (3679)	6576 (958)
2007	2346 (934)	28 958 (4088)	2253 (521)

[a] *Brachyramphus* murrelets that could not be identified to species during surveys.

Except for a smaller number of shoreline transects in 1989 (Agler *et al*. 1998), the same transects in all strata were surveyed every year that the PWS-wide survey was conducted between 1989 and 2007. The surveyed blocks amounted to 4.6% of the surface area of PWS waters (Agler *et al*. 1998).

Most surveys were conducted when wave height was <0.3 m (equivalent to Beaufort scale 0–2) and none were attempted in seas >0.6 m (roughly equivalent to Beaufort scale 3). One driver and two observers aboard each vessel recorded all birds and mammals within 100 m either side of and ahead of the boat. Observers were trained to estimate distances using rangefinders and a towed duck buoy. Radar was used to maintain proper distance from shore during shoreline surveys. Observers used binoculars to identify birds to the lowest possible taxon. For the purpose of calculating population estimates we assumed that detection probability was 100% and comparable across years because all observers were trained in distance estimation (i.e. <100 m or >100 m), species identification, and the importance of adhering to a strict protocol. In every year, observers had the option of recording a murrelet not identified to species as "unidentified *Brachyramphus*" (hereafter, unidentified murrelet). In later years, we emphasized training in distinguishing between Marbled and Kittlitz's Murrelets; thus, there was unequal emphasis on species identification, and the proportion of unidentified murrelets varied from 2% to 89%.

Data analysis

For each transect, we calculated density of birds (birds/km^2). For coastal-pelagic and pelagic blocks, we averaged the densities from the two secondary lines, and that density was applied to the area within each block (which varied owing to intersections with land). We calculated population estimates (Table 1; hereafter, "field estimates") and variances using a ratio estimator (Cochran 1977) on the densities for each stratum (shoreline, coastal-pelagic and pelagic; see Klosiewski & Laing 1994). We derived the total field estimates of Marbled, Kittlitz's and unidentified murrelets from the summed estimates and variances of each stratum.

Model of population trends

Using the field estimates and variances for Marbled, Kittlitz's, and unidentified murrelets, we developed a population model that incorporated unidentified murrelets and made predictions of population sizes based on the empirical data. The interpretation of trends was complicated by the fact that field estimates of both murrelet species from 1972 were considerably higher than in any subsequent year and were derived from data collected 17 years before the next series of surveys (Table 1). Two other years were unusual: in 1993, exceptionally high numbers of *Brachyramphus* murrelets (most not identified to species) were recorded, and, in 1998, exceptionally low numbers of Kittlitz's Murrelet (despite a high proportion of identified birds) were observed. Consequently, we modeled four sets of data from PWS-wide surveys (Table 1): (1) included all years; (2) excluded 1972; (3) excluded 1972 and 1993; and (4) excluded 1972 and 1998.

We used field estimates of population size and standard errors (SE; Table 1) to parameterize the models, which were designed to incorporate unidentified murrelets and to investigate the effects of inclusion and exclusion of anomalous survey years. Standard errors corresponded to the 95% confidence intervals (CI) calculated from the survey data (SE = CI/1.96). Our model assumed that the probability of being identified was the same for both species but may have differed from year to year. We assumed identifications to be correct—e.g. a bird identified as a Kittlitz's Murrelet was not a Marbled Murrelet. The model also assumed that Kittlitz's and Marbled murrelets have independent but constant trends over time.

Let $N_{K,0}$ and $N_{M,0}$ represent the unknown population estimates of Kittlitz's and Marbled murrelets, respectively, in the starting year, t_0. The symbols K_t, M_t, and U_t are the field estimates of Kittlitz's, Marbled, and unidentified murrelets, respectively, in year t. Let θ_K and θ_M be the annual population growth rate of Kittlitz's and Marbled murrelets, respectively, let γ_t be the probability that a bird was identified in year t, and let E_{K_t}, E_{M_t}, and E_{U_t} represent error terms (including discrepancies between predictions of the fitted model and the observations, and measurement error in the field). The model is then

$$K_t = N_{K,0}\,\theta_K^{t-t_0}\gamma_t + E_{K_t} \quad [1]$$

$$M_t = N_{M,0}\,\theta_M^{t-t_0}\gamma_t + E_{M_t} \quad [2]$$

and

$$U_t = \left(N_{K,0}\,\theta_K^{t-t_0} + N_{M,0}\,\theta_M^{t-t_0}\right)\left(1-\gamma_t\right) + E_{U_t} \quad [3]$$

Strictly speaking, model predictions for K_t, M_t and U_t are predicted numbers seen in surveys, not predicted population sizes, because unidentified birds and the annual identification probabilities were explicit in the model. To make the distinction clear, we henceforth refer to K_t, M_t, and U_t, whether from field or model estimates, using the term "survey estimate." We estimated the unknown parameters (N_K, N_M, θ_K, θ_M, γ_t) in the model above through a weighted least squares nonlinear regression analysis, choosing the parameter values that minimized the criterion Q,

$$Q = \sum_i \sum_t \frac{\left(Y_{i,t} - \hat{Y}_{i,t}\right)^2}{V_{i,t}} \quad [4]$$

where $Y_{i,t}$ was the field survey estimate for the ith group of birds at time t (i.e. either K_t, M_t, or U_t), $\hat{Y}_{i,t}$ was the corresponding predicted value and $V_{i,t}$ was the corresponding variance (the SE squared from Table 1). This method gave greater weight to survey estimates with lower variance; that is, such observations had greater influence on the regression parameter estimates than did observations with higher variance. For the nonlinear minimization, we used reasonable initial guesses based on available information. Initial values for N_K and N_M were taken from observed survey estimates in year t_0 (Table 1). In all analyses, initial values were $\theta_K = \theta_M = 1$, representing stable populations, and $\gamma_t = (K_t + M_t)/(K_t + M_t + U_t)$, the observed proportions of identified birds.

We obtained confidence intervals for our estimators by simulation. We assumed that field observations for all three groups of birds (Kittlitz's, Marbled and unidentified) were log-normally distributed with means and variances estimated from the field samples (Table 1). Under that assumption, replicate surveys were randomly generated 5000 times, and parameters were re-estimated from the simulated data sets using nonlinear regression. Confidence limits were calculated using the percentile method (Manly 2007); thus, the

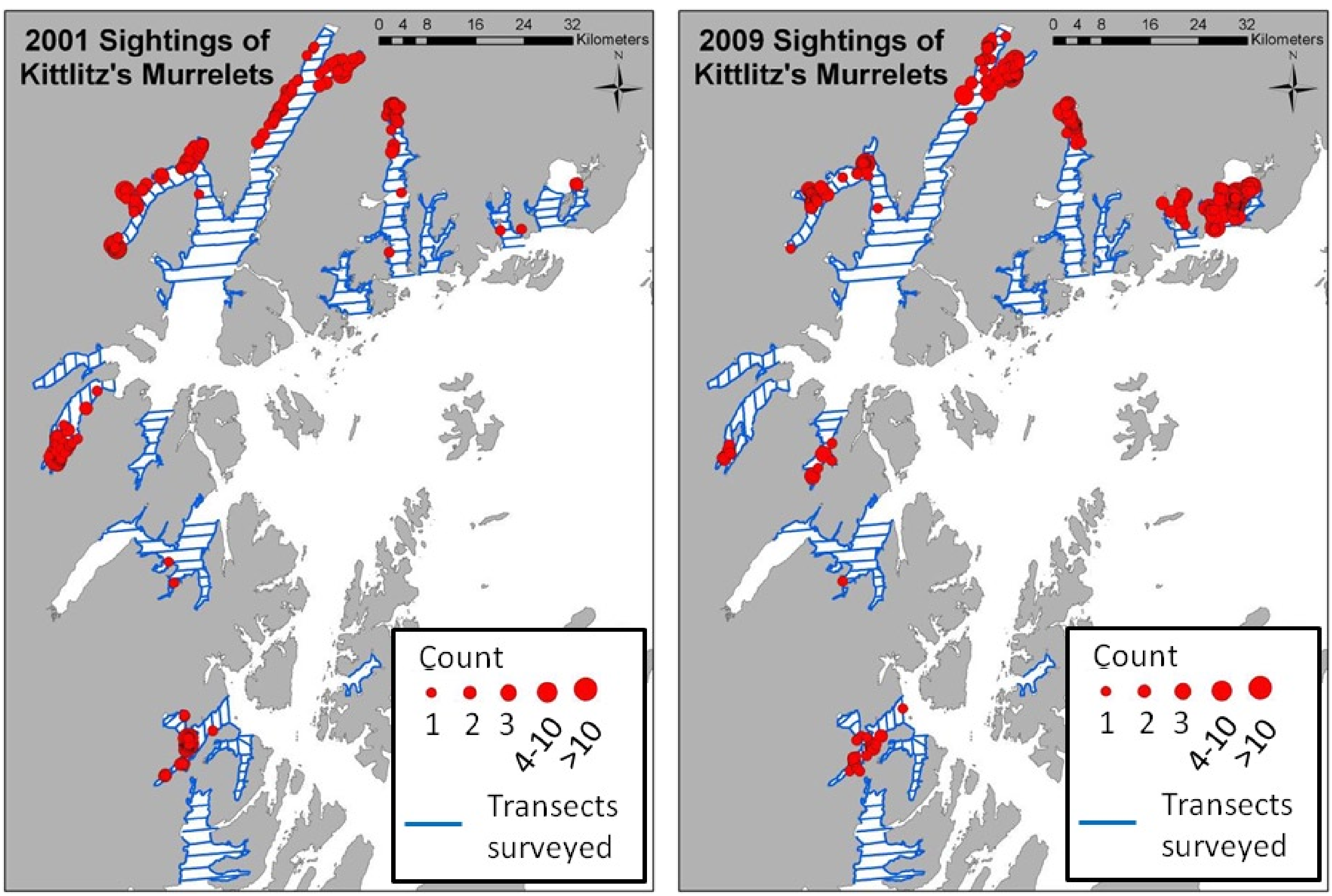

Fig. 2. Locations of transects (blue lines) used for intensive surveys of 17 bays and fjords in Prince William Sound, Alaska, 2001 and 2009. Locations of identified Kittlitz's Murrelets (red-filled symbols) are shown.

95% confidence interval was determined from the 2.5th and 97.5th percentiles of the simulation distribution.

We generated projections of model estimates (rather than survey estimates) using the simple exponential growth model implied by equations [1] and [2]. Model estimates of Kittlitz's Murrelet, $N_{K,t}$, and Marbled Murrelet, $N_{M,t}$ were calculated as

$$N_{K,t} = \hat{N}_{K,0}\hat{\theta}_K^{t-t_0} \qquad [5]$$

and

$$N_{M,t} = \hat{N}_{M,0}\hat{\theta}_M^{t-t_0} \qquad [6]$$

where all parameter estimates on the right side of the equations were obtained from the fitted nonlinear regression. We also modeled the predicted population size of total *Brachyramphus* murrelets to quasi-extinction (<100 birds). All analyses were conducted in Matlab (v7.11, MathWorks, Inc., Natick, MA).

Intensive surveys

Data collection

The study design used for the PWS-wide surveys was well-suited to abundant and widely dispersed species, such as the Marbled Murrelet, but not to the rare and patchily distributed Kittlitz's Murrelet. Field population estimates of Kittlitz's Murrelet had large SEs (Table 1) and wide CIs as a result of their clumped distribution. Thus Kendall & Agler (1998) suggested that future surveys for this species be stratified for suitable habitat. We followed their advice in 2001, designing "intensive" surveys specifically for Kittlitz's Murrelets (Kuletz *et al.* 2003), and repeated the same design in 2009. The intensive surveys (1 June–31 July) targeted 17 fjords and bays where Kittlitz's Murrelet had previously been observed or where there was suitable habitat but the area had not previously been surveyed intensively. In 2001 we surveyed five fjords 1–3 times, but in 2009 we conducted only a single survey of each bay; therefore, for present purposes, we used the survey date in 2001 that was closest to the 2009 survey date. Intensive surveys used the same protocol and vessel type as the PWS-wide surveys—strip-transect methodology, 200 m wide strip, 8 m vessels and continuous recording of all birds and mammals. However, study design differed in that the intensive survey comprised a continuous shoreline count in each fjord and a set of parallel, linear transects perpendicular to shore at approximately 2 km intervals (pelagic waters >200 m from shore ; Fig. 2). We used dLOG software (Glenn Ford Consulting, Portland, OR) to enter observations directly into a computer interfaced with a global positioning system, which allowed us to closely replicate the 2001 transects in 2009 (exceptions being caused by glacial ice or tidally exposed shallows).

Data analysis

For the intensive surveys, we calculated transect areas from the boat tracks recorded in dLOG. Using the shoreline track, we determined the total area surveyed within each fjord or bay and excluded from analysis areas that could not be surveyed due to ice or shallows. We

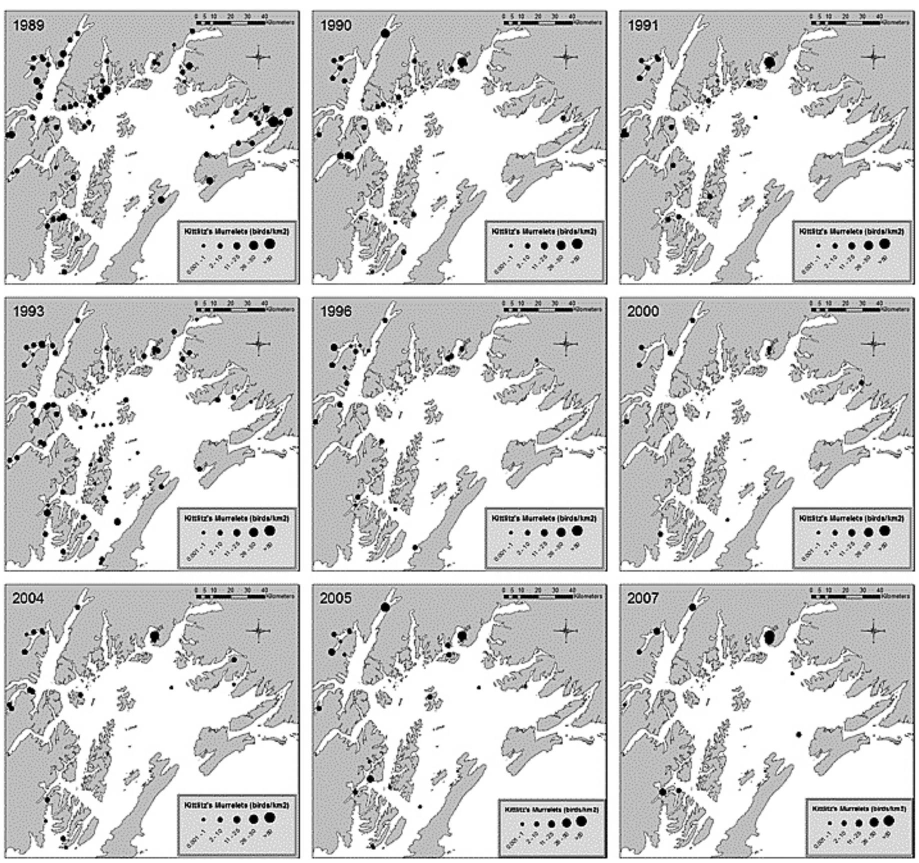

Fig. 3. Distribution of identified Kittlitz's Murrelets observed during PWS-wide surveys, 1989–2007. The same randomly selected transects were surveyed in all years. Not shown are maps for 1998, which had few identified Kittlitz's Murrelets, and 1972, which had a different set of randomly selected transects.

estimated abundance by dividing the pelagic Kittlitz's Murrelet count by pelagic area surveyed per fjord, resulting in a pelagic density (birds/km^2). We then multiplied the pelagic density in each fjord by the respective pelagic area of the fjord, and summed across fjords. Finally, we added the summed shoreline counts. We then used a custom nonparametric bootstrap function stratified by fjord to resample the original pelagic data set randomly with replacement while calculating a new abundance estimate for each iteration (n = 10 000 generated samples; R Development Core Team 2009). For each iteration, the transects contributing to the data sets for the two years were held constant. We then calculated the difference between the abundance estimate for 2009 and 2001 at each bootstrap iteration. We calculated upper (0.975) and lower (0.025) CIs from the bootstrapped distribution of abundance estimates to test if 95% of the distribution overlapped zero. For this analysis, we used only birds identified to species. Because the bays were not randomly selected we did not extrapolate to the whole of PWS—the scope of inference for the intensive survey results was limited to the 17 fjords and bays sampled.

TABLE 2

Counts of Kittlitz's Murrelets (KIMU), Marbled Murrelets (MAMU) and unidentified murrelets (UNMU), and densities of identified Kittlitz's Murrelets, in intensive surveys of selected bays and fjords in Prince William Sound, Alaska, 2001 and 2009[a]

Fjord	2001						2009					
	No. KIMU	No. MAMU	No. UNMU	KIMU density, no./km^2	Pelagic area surveyed, km^2	Total pelagic area[b], km^2	No. KIMU	No. MAMU	No. UNMU	KIMU density, no./km^2	Pelagic area surveyed, km^2	Total pelagic area[b], km^2
Blackstone Bay	7	158	1	2.24	3.08	35.02	7	4	7	1.88	3.73	34.67
Cochrane Bay	0	43	10	0.00	2.54	22.62	4	39	13	1.28	3.14	22.56
College Fjord	32	85	11	3.58	8.95	88.40	53	60	5	5.97	8.87	82.19
Columbia Bay	0	0	0	0.00	4.01	21.62	33	3	0	10.57	3.12	22.16
Eaglek Bay	0	58	0	0.00	4.11	30.98	0	71	2	0.00	3.79	28.53
Harriman Fjord	76	307	6	11.44	6.74	55.90	63	117	4	10.03	6.28	53.04
Heather Bay	1	0	0	1.21	0.85	7.84	8	23	3	10.29	0.78	6.54
Icy Bay	17	12	3	3.75	4.41	36.32	15	8	1	3.07	4.88	38.84
Long Bay	0	45	0	0.00	2.55	15.28	1	143	9	0.37	2.73	14.91
Passage Canal	0	33	0	0.00	2.66	24.65	0	0	0	0.00	2.51	23.59
Port Bainbridge	0	9	5	0.00	7.92	70.93	0	124	0	0.00	7.91	71.62
Port Nellie Juan	1	51	6	0.11	8.89	79.56	0	38	2	0.00	9.07	88.01
Port Wells	0	51	12	0.00	12.61	182.27	1	199	16	0.08	13.03	179.14
Unakwik Inlet	0	119	1	0.00	7.52	72.12	6	174	8	0.81	7.39	66.71
Wells Bay	0	33	2	0.00	2.10	23.22	0	29	4	0.00	2.10	23.43
Whale Bay	0	5	0	0.00	2.48	17.85	0	29	1	0.00	2.73	18.11
Drier Bay[c]	0	0	0	0.00	0.00	0.00	0	0	0	0.00	0.00	0.00
Total	134	1009	57		81.42	784.58	191	1061	75		82.06	774.05

[a] Estimate for each of 17 bays and fjords derived from birds counted, total area surveyed and total pelagic area. Shoreline (≤200 m from shore) counts excluded from calculations.

[b] Area for extrapolation in each fjord.

[c] Shoreline counts only (no pelagic counts) in Drier Bay (<400 m wide).

RESULTS

Distribution

In PWS-wide surveys, we found Kittlitz's Murrelets in deep fjords and bays of the northwestern Sound (especially Harriman and College fjords) and, to a lesser extent, in bays of the northcentral mainland (especially Columbia and Heather bays) and in southwestern fjords (Fig. 3). Kuletz *et al*. (2003) described a shift in Kittlitz's Murrelet distribution between 1989 and 2000; Kittlitz's Murrelets were previously found throughout PWS mainland fjords but became concentrated in the northwestern fjords. This new pattern of distribution remained basically the same during surveys in 2004, 2005 and 2007 (Fig. 3). The intensive survey in 2001 substantiated the recent importance of the northwestern fjords for Kittlitz's Murrelet (Fig. 2a), with four fjords having densities >1.2 birds/km^2 (Table 2), accounting for 98% of the Kittlitz's Murrelet population estimate. In 2009, Kittlitz's Murrelets were more widespread, with eight fjords having densities >0.8 birds/km^2 (Table 2), accounting for 98% of the population. In 2009, Columbia Bay ranked first among fjords in Kittlitz's Murrelet abundance, followed by Harriman and College fjords (Fig. 2b, Table 2).

Field estimates of population size and trend

Field estimates from the most recent (2007) PWS-wide survey were 2346 (95% CI 514–4178) Kittlitz's Murrelets and 28 958 (20 945–36 971) Marbled Murrelets, plus an additional 2253 (1231–3275) unidentified murrelets (Table 1). Between 1989 and 2007, the PWS-wide field estimates for identified birds showed a decline of 62% for Kittlitz's Murrelet (5.0% per annum). With the addition of 1972 data (35–year span), field estimates indicated a 97% decline, at an average rate of 10.6% per annum. Intensive surveys (Fig. 4) revealed a statistically significant increase in Kittlitz's Murrelets between 2001 (1400 birds; 95% CI 977–1889) and 2009 (2080 birds; 95% CI 1409–2990), with wide confidence intervals in both years.

Model estimates and trends

Using field estimates from the PWS-wide surveys, our model's parameter estimates (which incorporated unidentified birds) showed that populations of both Marbled and Kittlitz's murrelets declined (all θ <1.0; Table 3). The estimated rate of decline was greater for Kittlitz's than for Marbled murrelets, and θ_M was larger than θ_K in all scenarios (with or without data from 1972, 1993 and 1998), despite the variability in those parameters (Table 3). In addition, Marbled Murrelet estimates had narrower confidence limits than Kittlitz's Murrelet under all scenarios (Table 3). Using data from all years (Table 1), the estimated growth rate of Kittlitz's Murrelet (θ_K) was 0.82, a decline of 18.1% per year. Excluding data from 1972, or both 1972 and 1993, resulted in lower estimates of θ_K, 0.7002 and 0.6980, respectively (declines of 30.0% and 30.2% per year). This result (steeper population declines with the exclusion of the initial large survey estimate from 1972) was primarily due to the influence of both the low count and associated low variance in 1998. Thus, excluding data from 1998 reduced the decline to θ_K = 0.87, or 13.1% per year.

For Marbled Murrelets, the estimates of θ_M were similar (~0.94) in all four cases (Table 3), indicating a decline of about 5.5% per year. Likewise, for years in common, the estimated proportions of birds identified, γ_t, were similar among different models. Initial population estimates of Kittlitz's ($N_{K,0}$) and Marbled ($N_{M,0}$) murrelets differed substantially depending on the starting year, primarily because 1972 had much higher field estimates than later years (Table 1).

Comparison of model and field estimates

In most cases, the model estimates appeared to fit the field estimates reasonably well, although Kittlitz's Murrelet tended to show greater discrepancies than Marbled or unidentified murrelets (Fig 5), especially in 2005 and 2007 (Fig. 5a). The model indicated a decline in survey estimates of Kittlitz's Murrelet regardless of whether data from 1972 (Fig. 5) or 1993 (not shown) were included or not. In contrast, when 1972 and 1998 were omitted, the field estimates diverged less from predicted estimates after year 2000 (compare Fig. 5a,b with Fig. 5c). Patterns in survey estimates of Marbled Murrelet were less clear, particularly when data from 1972 were excluded (Fig. 5e,f). The decline in unidentified murrelets after 1993 (Fig. 5g–i) reflected both greater success in species identification (note larger estimates for γ in 1996–2007 than 1989–1993 in Table 3) and the decline in total *Brachyramphus* survey estimates (Table 4)—with fewer total murrelets, there were fewer unidentified murrelets. In contrast to Kittlitz's Murrelet, results for Marbled and unidentified murrelets (most of which would have been Marbled Murrelets) were less affected by exclusion of the 1972, 1993 or 1998 data.

Projected trends

Parameter estimates from the fitted model were used to project population sizes (Table 4) and trends of Kittlitz's and Marbled murrelets (Fig. 6). (Note that the Y-axis in Figure 6, as in Figure 5, is on a log-scale). Assuming Kittlitz's Murrelet had an initial 1972 population of $N_{K,0}$ = 91 161 (Table 3, including all years), the model estimate of θ_K led to a predicted population of 84 birds in 2007, below the quasi-extinction threshold of 100 birds. Starting with the 1989 model estimate of 6721 Kittlitz's Murrelets, and excluding 1972 and 1998 (θ_K = 0.87; Table 3), the model yielded a predicted

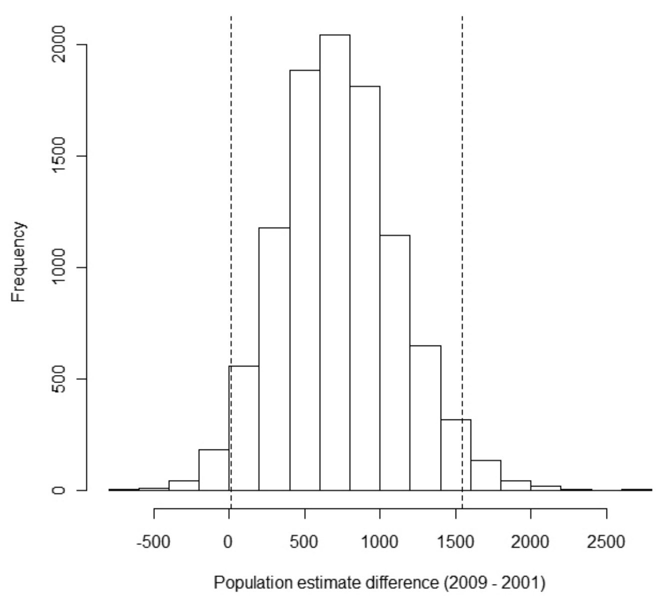

Fig. 4. Frequency distribution of the difference between Kittlitz's Murrelet abundance estimates from intensive surveys in 2001 and 2009 (and 95% confidence intervals of the difference). Abundance estimates used a ratio estimator; 95% CI were generated from the frequency distribution of 10 000 bootstrapped samples.

population of 533 in 2007 (Table 4), well below the field estimate of 2346 (Table 1). The latter scenario predicted quasi-extinction in 2019 at a population size of 98.

DISCUSSION

Comparison of model and field estimates and trends

Both field and model estimates indicated declining populations of total *Brachyramphus* murrelets (most of which were likely Marbled Murrelets) in PWS. Modeled trends suggested that Kittlitz's Murrelet has declined faster than the more abundant Marbled Murrelet. Any prediction of extirpation or quasi-extinction must be qualified by the assumption of a constant rate of change in population size, which may be unrealistic, and by the uncertainty in the model estimates of population growth rate. Incorrect prediction was evident in the model estimates for Kittlitz's Murrelet. An earlier model (Kuletz *et al*. 2005; data from 1972 through 2004) predicted fewer than 100 birds by 2007, whereas our field estimate that year was ~2300 birds (Table 1). With the two additional years of data showing increases in the field (2005 and 2007), and with the low estimate of 1998 removed, our model predicted quasi-extinction (<100 birds) of Kittlitz's Murrelet in approximately year 2019. While population sizes predicted far in the future are inherently unreliable, steep declines predicted in the model were consistent with trends in field estimates for identified birds.

Low counts and low variance in 1998 greatly influenced our model estimates and predicted trend for Kittlitz's Murrelets. The predicted trend, though improved with 1998 removed, remained negative despite the upward change in 2005 and 2007 (Fig. 6). Projections for Marbled Murrelet were similar whether data from 1972, 1993 or 1998 were included. Using data from all years, a starting population of 236 672, and $\theta_M = 0.94$ (Table 3), the projected population of Marbled Murrelets in 2007 was 34 165 birds (Table 4). Because of that relatively modest rate of decline and a larger initial population, a population of fewer than 100 birds is not predicted to occur before 2110. The modeling exercise illustrates the relative sustainability of a large population undergoing moderate decline (i.e. Marbled Murrelet) contrasted with a small population experiencing rapid decline (i.e. Kittlitz's Murrelet).

Model population estimates were much closer to field population estimates for Marbled Murrelet (e.g. ~34 000 birds predicted in 2007 versus the field estimate of ~29 000 birds) than for Kittlitz's Murrelet. Inclusion of the 1972 data did not change the predicted trend of Marbled Murrelet but reduced the estimated decline of Kittlitz's Murrelet. Although the 1972 survey used different transects, the set constituted a valid random sample that should yield unbiased population estimates for both murrelet species. The 1972 field estimates also offer the advantage of expanding our time frame to bracket the *Exxon Valdez* oil spill in 1989. Kuletz *et al*. (2003) reported an 84% decline in Kittlitz's Murrelets between 1989 and 2000, but including the 1972 survey and years since 2000 reduces the rate of decline. Including the 1972 survey suggests declines in both species began before the oil spill, although for Kittlitz's Murrelet the rate of decline may have accelerated during the 1990s. The last two PWS-wide surveys (Table 1) and the intensive surveys

TABLE 3
Model parameter estimates from simulated July survey data for Kittlitz's and Marbled murrelets, Prince William Sound, Alaska, 1972–2007

Parameter[b]	Mean (95% CI)[a]			
	All Years	Excluding 1972	Excluding 1972 and 1993	Excluding 1972 and 1998
$N_{K,0}$	91 161 (45 619–186 104)	9057 (5151–14 359)	8634 (4426–14 178)	6721 (3556–11 131)
$N_{M,0}$	253 944 (217 640–295 487)	96 018 (87 643–104 970)	94 561 (86 247–103 499)	96 958 (88 209–106 205)
θ_K	0.8190 (0.7918–0.8415)	0.7002 (0.6373–0.7717)	0.6980 (0.6171–0.7830)	0.8687 (0.8070–0.9300)
θ_M	0.9443 (0.9383–0.9504)	0.9432 (0.9345–0.9523)	0.9438 (0.9351–0.9528)	0.9433 (0.9345–0.9519)
γ_{1972}	0.9859 (0.9560–0.9971)	–	–	–
γ_{1989}	0.5972 (0.5271–0.6644)	0.6115 (0.5436–0.6765)	0.6087 (0.5413–0.6712)	0.6087 (0.5413–0.6719)
γ_{1990}	0.5430 (0.4764–0.6107)	0.5567 (0.4914–0.6192)	0.5542 (0.4863–0.6198)	0.5555 (0.4898–0.6199)
γ_{1991}	0.4356 (0.3518–0.5269)	0.4176 (0.3350–0.5047)	0.4217 (0.3355–0.5176)	0.4078 (0.3197–0.4995)
γ_{1993}	0.1805 (0.1279–0.2444)	0.1847 (0.1313–0.2521)	–	0.1870 (0.1350–0.2542)
γ_{1996}	0.7631 (0.6675–0.8426)	0.7630 (0.6699–0.8411)	0.7621 (0.6649–0.8409)	0.7611 (0.6710–0.8363)
γ_{1998}	0.9413 (0.8979–0.9682)	0.9421 (0.8975–0.9705)	0.9433 (0.8984–0.9705)	–
γ_{2000}	0.9799 (0.9554–0.9930)	0.9800 (0.9554–0.9928)	0.9794 (0.9542–0.9931)	0.9801 (0.9554–0.9928)
γ_{2004}	0.9792 (0.9688–0.9868)	0.9789 (0.9682–0.9866)	0.9787 (0.9677–0.9866)	0.9795 (0.9694–0.9870)
γ_{2005}	0.8326 (0.7818–0.8759)	0.8296 (0.7737–0.8734)	0.8290 (0.7745–0.8740)	0.8340 (0.7803–0.8780)
γ_{2007}	0.9330 (0.8979–0.9579)	0.9318 (0.8964–0.9577)	0.9318 (0.8957–0.9573)	0.9334 (0.8992–0.9585)

[a] 95% confidence interval determined by the percentile method.
[b] *N* is population estimate of Kittlitz's (*K*) or Marbled (*M*) in 1972 (t_0), θ is the annual population growth rate, and γ is the probability a bird was identified in year *t*.

in 2001 and 2009 (Fig. 4) suggest Kittlitz's Murrelet numbers may have stabilized by the late 2000s, but more data are needed to confirm that possibility.

Survey implications

PWS-wide surveys

It is unlikely that the observed spike in numbers in 1993, or the relative absence of birds in 1998, were due to abrupt changes in recruitment or breeding population size. Those anomalies might have arisen from sampling error, changes in distribution within PWS that affected field estimates, or temporary immigration or emigration from PWS reflecting oceanographic events in PWS or elsewhere. The PWS-wide surveys all used the same transects, platforms and protocol; thus, the main source of sampling error was likely the proportion of unidentified murrelets. The modeling effort was our attempt to deal with this issue.

Changes in distribution—e.g. birds dispersing over pelagic waters and concentrating less in the upper fjords—could reduce inter-transect variation, affecting both population estimates and the ability to detect trends (Cochran 1977). Notably, the only year with substantial numbers of Kittlitz's Murrelets in pelagic areas was 1993 (Fig. 3), when the field population estimate was relatively high (Table 1).

Kissling *et al*. (2007) recommended two surveys annually and a minimum of 50 km of transects. The PWS-wide surveys were conducted once during each sampled year and assumed that birds were not biased in their movement within PWS. We consider that >325 randomly selected transects totaling nearly 1800 km were probably little affected by shifts in distribution within PWS over the course of the 3-week survey. Kissling *et al*. (2007) also determined that annual surveys over 15 years would have high power (>0.9) to detect a 5% annual decline. The 10 surveys conducted since 1989 in PWS approached that sample size, but the surveys were spread over 19 years; given observed interannual variability in population estimates, we recommend additional surveys to verify the trends.

Although our surveys covered a large geographic area, the extent of murrelet movement between PWS and the GOA is unknown. It is possible that broad-scale movements differed among years, resulting in fluctuations in population size within PWS. For example, the unusually high numbers of murrelets present in July 1993 coincided with El Niño conditions that reduced murrelet numbers in regions of British Columbia and Oregon (Alger *et al*. 1998). During that event, adjacent waters in the Gulf of Alaska were anomalously warm but PWS remained relatively cool (Piatt & Van Pelt 1997, Pearson *et al*. 1999). Cooler waters may have attracted prey and predators from elsewhere. Conversely, the low number of Kittlitz's Murrelets in 1998 may reflect changes in oceanographic conditions, prey, and seabirds throughout the GOA in 1998–1999 (Litzow 2006, Shultz *et al*. 2009). Such anomalies highlight the importance of continued monitoring, especially for highly mobile species such as the Kittlitz's Murrelet, which may have a low breeding propensity (Day *et al*. 1999, M. Kissling, US Fish and Wildlife Service, Juneau, Alaska, unpublished data).

Intensive surveys

In 2009, Kittlitz's Murrelets occupied the same fjords they had in 2001 (Fig. 2), but with a substantial shift in numbers from Harriman Fjord to others, primarily Columbia and Heather bays. The latter two bays are the terminus for the Columbia Glacier, one of the largest and most rapidly receding glaciers in PWS (Molnia 2001). Although the 2001 intensive survey found most Kittlitz's Murrelets in fjords with stable or increasing glaciers (Kuletz *et al*. 2003), the high density of birds in Columbia Bay in 2009 suggests that a complex set of factors affects the distribution of Kittlitz's Murrelet (Kissling *et al*. 2007). Indeed, Kendall & Agler (1998) found the highest mean density of Kittlitz's Murrelet for any transect in PWS (30.70 birds/km^2 averaged across the years 1989–91, 1993 and 1996) near Columbia Glacier.

TABLE 4
Modeled population estimates for *Brachyramphus* murrelets in July in Prince William Sound, Alaska[a,b]

Year	Kittlitz's Murrelet				Marbled Murrelet			
	All Years	Excluding 1972	Excluding 1972 and 1993	Excluding 1972 and 1998	All Years	Excluding 1972	Excluding 1972 and 1993	Excluding 1972 and 1998
1972	91 161	–	–	–	253 944	–	–	–
1989	3059	9057	8634	6721	95 853	96 018	94 561	96 958
1990	2506	6341	6027	5838	90 514	90 565	89 247	91 460
1991	2052	4440	4207	5072	85 473	85 421	84 231	86 275
1993	1376	2177	–	3827	76 216	75 992	–	76 768
1996	756	747	697	2509	64 177	63 765	63 077	64 437
1998	507	366	340	–	57 227	56 727	56 187	–
2000	340	180	165	1429	51 029	50 466	50 049	51 019
2004	153	43	39	814	40 575	39 940	39 711	40 395
2005	125	30	27	707	38 315	37 672	37 479	38 105
2007	84	15	13	533	34 165	33 514	33 385	33 906

[a] Projections account for unidentified *Brachyramphus* murrelets.
[b] Model used to generate predictions assumes a constant rate of change.

Further work is needed to determine what changes in oceanography and prey may have influenced interannual or decadal shifts in the distribution of Kittlitz's Murrelet in PWS.

Comparison of PWS-wide and intensive surveys

Our intensive surveys of 17 fjords used by Kittlitz's Murrelets resulted in population estimates similar to those obtained via PWS-wide surveys of randomly selected transects. That held true whether comparing the 2000 PWS-wide survey (1033 birds) to the 2001 intensive survey (1400 birds) or comparing the 2007 PWS-wide survey (2346 birds) to the 2009 intensive survey (2080 birds). Intensive surveys, however, had tighter confidence intervals, which would aid the detection of trends (Cochran 1977). Nonetheless, the similarity in results with our intensive surveys suggests the PWS-wide surveys did a reasonable job of tracking trends of Kittlitz's Murrelets. Given wider confidence limits, the usefulness of PWS-wide surveys relies heavily on adherence to a consistent protocol and regularly timed effort over many years. The model presented here offers a way to derive population estimates for a rare species commingled with an abundant one, when species identification is a source of error. Additionally, adequate training and experienced personnel are important to increase identification rates in the field.

Management implications

Possible reasons for observed trends

The long-term decline of two *Brachyramphus* species suggests that a regional, contemporaneous alteration in their environment may be responsible. Kittlitz's Murrelets nest in remote alpine areas with little human impact (Day *et al*. 1999), and alteration of known nesting habitat has not been documented. Among tree-nesting Marbled Murrelets, loss of old-growth forest has been implicated in declining numbers farther south (Burger 2002, McShane *et al*. 2004). As the amount of past and current timber harvest in PWS is comparatively small (Kuletz *et al.* 2005), it seems likely that declines of *Brachyramphus* murrelets in PWS are more related to changes in the marine environment. In the GOA, prey species composition and abundance have changed since the 1970s (Anderson & Piatt 1999), and such changes in PWS may explain population declines in piscivorous birds (Agler *et al*. 1999), including *Brachyramphus* murrelets.

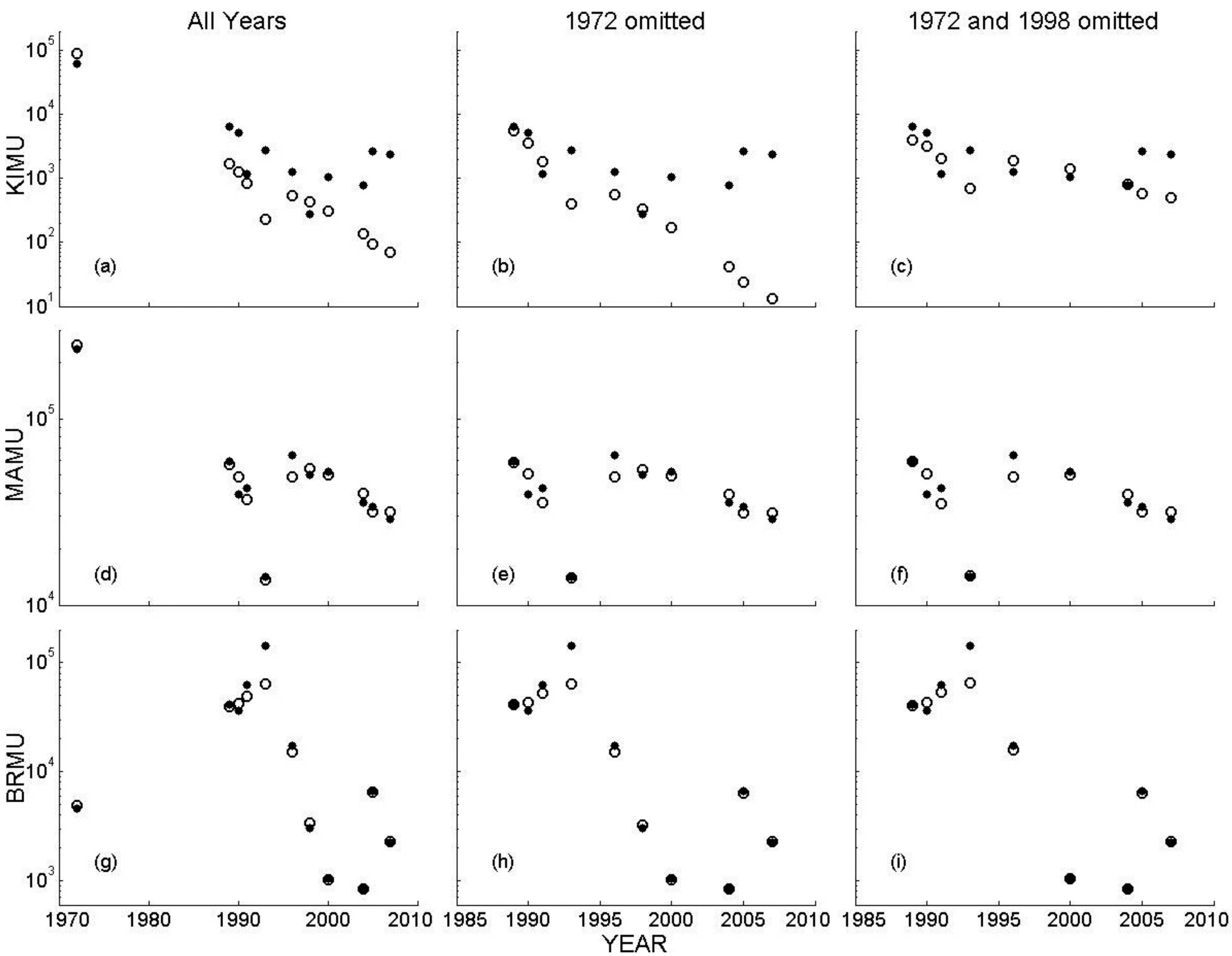

Fig. 5. Field estimated (filled symbols) and predicted (open symbols) survey numbers in July of Kittlitz's Murrelets (KIMU; a–c, first row), Marbled Murrelets (MAMU; d–f, second row), and unidentified murrelets (UNMU; g–i, third row) under three scenarios of data inclusion/exclusion. Predicted values obtained from a nonlinear regression model. Open symbols obscured by closed symbols in some cases.

In addition to possible changes in prey, human activities such as commercial gillnet fishing, recreational boating and tourism have increased in PWS since the 1980s (Murphy *et al*. 2004). Large tour vessels travel specifically to fjords with tidewater glaciers where Kittlitz's Murrelets forage (Day *et al*. 2003, Kuletz *et al*. 2003). Gillnet fishing has entangled and killed both murrelet species in PWS (Wynne *et al*. 1992), and even small boats can disturb murrelet foraging (Speckman *et al*. 2004). Minor oil spills occur regularly in PWS, and in 1989 the massive *Exxon Valdez* spill caused direct mortality of at least 8400 *Brachyramphus* murrelets (Kuletz 1996). Although most of that total was likely Marbled Murrelets (Carter & Kuletz 1995), a minimum of 370 Kittlitz's Murrelets killed directly by the spill (Kuletz 1996) constituted a greater proportion of that species' population (Day *et al*. 1999). Additional factors of unknown importance in PWS include the crash of Pacific herring *Clupea pallasii* stocks after 1993 and possible competition between

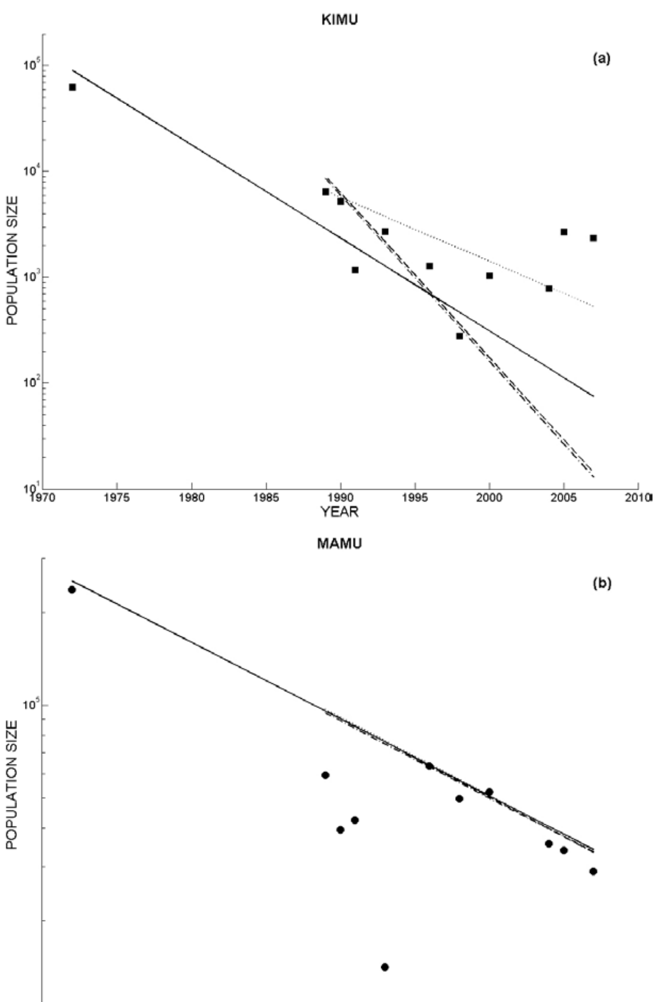

Fig. 6. Population projections based on equations [5] and [6] and model estimates of initial population size and growth rates for: (a) Kittlitz's Murrelets (KIMU), and (b) Marbled Murrelets (MAMU) in July surveys. Separate analyses for all years (solid lines), 1972 data excluded (dashed lines), both 1972 and 1993 data excluded (dash-dot lines), both 1972 and 1998 data excluded (dotted lines). Actual survey results shown by filled symbols. Lines with similar slopes overlay each other (e.g. exclusion of 1972 and exclusion of both 1972 and 1993 for KIMU, and all four data selection scenarios for MAMU).

juvenile herring and hatchery-reared salmon (Pearson *et al*. 1999) as well as possible long-term damage from the *Exxon Valdez* oil spill (Peterson *et al*. 2003).

Management and conservation concerns

Because Kittlitz's Murrelets are a small portion of all *Brachyramphus* murrelets in PWS, their population trend might increase or decrease without affecting the trend of the genus. Similar situations have occurred in fisheries; an aggregate trend (combined species) remained stable, even as some species within the aggregate declined or went extinct before managers could act (Ludwig *et al*. 1993, Dulvy *et al*. 2000, 2003, Harwood & Stokes 2003). The possibility of masked trends and crypto-extinctions, while documented for invertebrates and fish, is not often considered for marine birds. Birds that are inconspicuous when nesting, like the Kittlitz's Murrelet, share some characteristics that contribute to crypto-extinctions in fish—they are widely dispersed in uninhabited areas most of the year, difficult to encounter and enumerate and may change distribution in response to a dynamic and structurally complex habitat (Croxall & Rothery 1995).

As a population declines, fluctuations in size increase the probability of extinction, particularly for vertebrates numbering in the low thousands (Reed & Hobbs 2004), which is true of Kittlitz's Murrelet in PWS. Furthermore, rapid decline, regardless of population size, may be a sufficient cause for listing species and commencing recovery actions (International Union for Conservation of Nature and Natural Resources 2001). Trends observed in Marbled and Kittlitz's murrelets over three decades in PWS suggest that both *Brachyramphus* species should be conservation priorities. Whether Kittlitz's Murrelets have slowed or reversed a sustained downward trend can be determined only by additional monitoring. Concurrently, we should examine the reasons for changes in distribution and numbers during the past decade, in support of future conservation efforts.

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