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Habitat associations of marbled murrelets during the nesting season in nearshore waters along the Washington to California coast

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ABSTRACT

The marbled murrelet (*Brachyramphus marmoratus*) is a seabird in the family Alcidae that forages in nearshore waters of the Pacific Northwest, and nests in adjacent older-forest conifers within 80 km offshore. The species is of conservation concern due to habitat loss and declining numbers, and is listed as Threatened in British Columbia, Canada and in the United States portion of its range south of Canada. Recent monitoring in the United States indicated that murrelet numbers continued to decline there, especially in the waters of Washington State. To better understand this decline, and to inform conservation planning for the species, we evaluated how terrestrial and marine factors influence the distribution and abundance of the murrelet in coastal waters, including whether at-sea hotspots of murrelet abundance exist. Murrelet at-sea abundance and distribution were determined by surveys conducted annually from 2000 to 2012 in coastal waters from the United States–Canada border south to San Francisco Bay. We summarized mean and variance of murrelet density at the scale of 5-km segments of coastal waters throughout this area. We used a boosted regression tree analysis to investigate the contributions of a suite of marine and terrestrial attributes to at-sea murrelet abundance in each segment. We observed several regional hotspots of higher murrelet abundance at sea. Terrestrial attributes made the strongest contribution, especially the amount and cohesiveness of suitable nesting habitat in proximity to each segment, whereas marine attributes explained less of the spatial and temporal variations in murrelet abundance. At-sea hotspots of murrelet abundance therefore reflect not only suitable marine foraging habitat but primarily the proximity of suitable inland nesting habitat.

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1. Introduction

Spatial and temporal factors that influence the distribution and abundance of species are of considerable interest to effective conservation planning. Identifying hotspots of abundance can help identify areas to focus protection or other conservation measures (Amorim et al., 2009; Barbaree, 2011; Game et al., 2009; Nur et al., 2011; Suryan et al., 2012). Knowledge of these factors can also help us understand potential areas of conflict between human uses and important habitats to species (Winiarski et al., 2013). For example, understanding seabird distribution can help select locations for alternative energy developments (wave, tidal, wind) that minimize impacts to seabirds (e.g., Fox et al., 2006; Winiarski et al., 2013). In addition, understanding habitat relationships helps identify the factors that, if they can be manipulated, might be managed to have the greatest influence on population distribution and abundance.

The marbled murrelet (*Brachyramphus marmoratus*), a seabird in the Alcidae family, forages in nearshore waters along the coast of North America from the Aleutian Islands south to central California. It was declared Threatened under the United States Endangered Species Act (ESA) in the portion of the range from the Washington–British Columbia border to the southern end of its range (USFWS, 1997). As a result of the murrelet's legal status, there is great interest in understanding its biological status and trend as well as the factors that act as stressors on the population and that may contribute to species recovery. Unlike other seabirds, the murrelet nests up to 80 km inland, generally on the limbs of older coniferous trees but occasionally on the ground or on cliffs. Because of its inland nesting behavior and distance constraints on how far it forages from nests, the at-sea distribution of murrelets, especially during the nesting season, is likely to be influenced by the distribution of suitable nesting habitat. A nesting murrelet can be thought of as a central place forager (Orians and Pearson, 1979) with the nest as the central place. Other alcids, such as the common murre (*Uria aalge*), are colonial nesters and forage from a fixed colony site. In that case, available foraging habitat is subject to energetic constraints and is

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therefore restricted to some radius around the colony location (Burke and Montevecchi, 2009; Elliott et al., 2009). The murrelet, however, is not a colonial nester, but similar constraints may apply (Raphael et al., 2011; see the Methods section 2.2).

Given the dispersed distribution of the murrelet's nesting habitat, we were interested in how the amount of that habitat influences the local at-sea abundance of the murrelet during the breeding season. Marine conditions, specifically the amount of suitable prey, should also affect the at-sea distribution of murrelets (Ainley et al., 1995; Haynes et al., 2011), but previously we did not know the relative strength of influence of marine versus terrestrial habitat features on their distribution. We were also interested in the functional shape of the relationship between murrelet at-sea abundance and marine or terrestrial habitat features, as well as interactions between habitat features. To investigate these questions, we developed a statistical model relating murrelet abundance at sea to a suite of both marine and terrestrial attributes.

2. Methods

2.1. Marbled murrelet abundance

As part of the Effectiveness Monitoring Program for the Northwest Forest Plan (Huff et al., 2006; Raphael, 2006), we counted murrelets in nearshore waters from small boats by using line transect methods with distance estimation to account for detectability (Buckland et al., 2001; Raphael et al., 2007). We followed at-sea transects within primary sampling units (PSUs) that were roughly rectangular areas of about 20 km of coastline and that were generally contiguous over the entire sampling area. We divided each PSU into nearshore and offshore subunits corresponding to changes in murrelet density with distance from shore; the nearshore subunit was further subdivided into 4 5-km segments. Transect lines in each segment were parallel to shore and located at randomly assigned distances from shore up to 1.5 or 2.0 km from shore depending on location (Fig. 1; see Raphael et al., 2007 for details). Offshore transects were laid out in a zig-zag pattern out to a maximum of 8 km from shore (Fig. 1). For this study we restricted our analysis to the nearshore segments as these had the most complete coverage and because murrelet density decreases with distance from shore. Sampling began in year 2000 and extended to year 2012. All samples were obtained between May 15 and July 31, a period that corresponds with murrelet nesting.

We used the software program DISTANCE (Thomas et al., 2010) to estimate density of murrelets in each segment each year. We computed a detection function based on the distribution of sighting distances to each group of murrelets, an estimate of group size, and the exact transect length for each segment. We then computed the area of each segment based on length along coast and overall distance from shore

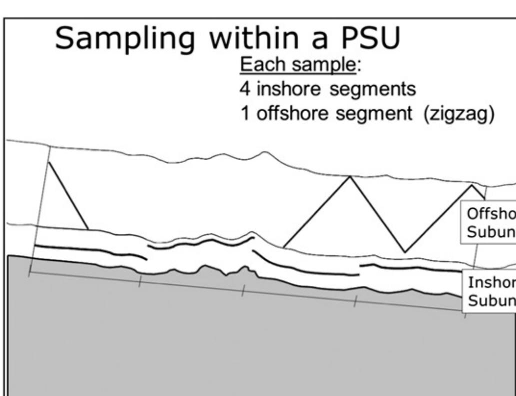

Fig. 1. Layout of at-sea transects used to estimate density of marbled murrelets. In this study, we analyzed data from only the inshore subunits.

and multiplied density by that area to compute abundance (estimated number of murrelets per segment).

To identify murrelet "hotspots" (Nur et al., 2011; Sydeman et al., 2006) along the coast, we examined patterns of mean and coefficient of variation (CV) in murrelet abundance; the CV provides a measure of temporal variability in abundance. We defined coastal hotspots as those 5-km segments that had higher mean abundance (upper 20th percentile of all segments) and lower CVs (lowest 20%).

2.2. Covariates

We calculated all covariates annually from 2000 to 2012 for each at-sea survey segment. Covariates varied spatially (by segment), temporally (by year), or both spatially and temporally (Table 1). Covariates were also associated with either marine foraging habitat suitability or terrestrial nesting habitat suitability (Table 1).

The first three marine covariates in Table 1 were based on proximity to terrestrial features that may influence observed at-sea abundance of murrelets, presumably due to effects on foraging conditions. These included the mean perpendicular distance (m) from the survey transect to shore for all at-sea surveys in a segment for the given year, the distance (km) from the survey segment center to the nearest major river (defined by a flow >166 ft^{-3} [4.7 m^{-3}] based on the USGS Enhanced River Reach Data 2.0 from 2003), and the predominant shoreline type. Shorelines were classified based on the Environmental Sensitivity Index (NOAA, 2002), which categorizes shorelines into 21 major classes. We simplified these into 11 classes and then calculated the predominant shoreline type within each survey segment boundary. This calculation resulted in 7 types represented in our study area (Table 2).

The remaining marine covariates in Table 1 were based on oceanographic conditions that may influence prey availability (primarily fish) and therefore murrelet abundance at sea. Because foraging conditions within each survey segment are likely to be influenced by marine conditions at broader scales, we calculated the remaining marine covariates that vary spatially based on the mean or sum (depending on the covariate) of values within a 10-km moving window. We then extracted the mean values of the moving window result within each survey segment (i.e., the mean of all moving window centers that fell within the segment boundary).

We obtained monthly mean sea surface temperature (SST) and chlorophyll-*a* concentration (ChlorA) data from the NASA Earth Observations (2012) portal. Data from 2000 to 2002 were collected by the SeaWIFS platform and data from 2003 to 2012 were collected from the MODIS Aqua platform (http://aqua.nasa.gov/about/instrument_modis.php). We then calculated the mean SST (°C) and ChlorA concentration (mg/m^3) within 10 km of the survey segment during two seasons, summer (values from May to July) and winter (values from Dec to Feb). All data were raster images with a resolution of 0.1° latitude/longitude.

We quantified marine human footprint based on a raster model of human threats to marine ecosystems (Halpern et al., 2008), including commercial shipping, pollution, commercial and recreational fishing, climate change (ocean acidification, ultraviolet radiation, and changes in sea temperature), invasive species, and benthic structures. This covariate was calculated based on the mean value within 10 km of the survey segment.

To quantify bathymetric influences on murrelet abundance, we used two approaches. First, we calculated the mean depth within 10 km of the survey segment based on a 250-m digital elevation model (USGS). Second, based on the same bathymetric data, we summed the area (km^2) of depths suitable for foraging within 10 km of the survey segment, hereafter referred to as "foraging area." Suitable foraging depths were based on a threshold (<25 m deep, except for the San Juan Islands and northern Puget Sound, for which the threshold was <40 m); the thresholds were based on natural breaks observed in the plots of murrelet abundance versus depth.