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A large-scale model for the at-sea distribution and abundance of Marbled Murrelets (*Brachyramphus marmoratus*) during the breeding season in coastal British Columbia, Canada

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Abstract

The role that the marine environment plays in the distribution and abundance of Marbled Murrelets (*Brachyramphus marmoratus*), a seabird which nests in old-growth forests, is not well understood. Therefore, we investigated how Marbled Murrelet marine distribution and abundance is related to the abiotic and biotic components of the marine environment. Data on the marine distribution of Marbled Murrelets in British Columbia (BC), densities (birds/km^2; 1972–1993), counts (number of birds per survey; 1922–1989), and pertinent environmental variables as identified from the literature were compiled and then organized in a Geographic Information System (GIS). On a 10 km scale, count surveys were not correlated with density surveys ($r^2 = 0.01$, $P = 0.46$). This suggests the interpretation of count survey data (relative abundance) should be done with care; and it is not further used in this study.

We built a parsimonious model to explain marine densities with marine predictors. First, significant predictors were identified with multivariate Generalized Linear Models (GLMs) by evaluating the shortest distances from survey locations to predictor variables. Murrelet density is higher close to sandy substrate, estuaries and cooler sea temperatures, and lower close to glaciers and herring spawn areas. Model predictors selected by using P

of 170,500 birds for the marine habitat of coastal BC. An additional, a posteriori predictor, the shortest distance to old-growth forest, explained much of the remaining residual variance. This model result led us to a hypothesis of how Marbled Murrelet distribution and abundance relates to proximity to old-growth forests, and it makes an initial basic link between the marine and terrestrial aspects of Marbled Murrelet habitat. Our approach presents the first predictive abundance and distribution models applied to Marbled Murrelets on a large scale (British Columbia coast). Our approach is robust, and the statistical algorithms compared here are fully described and are known to perform well. Our findings are crucial for decision making and consider conservation management on a scale pertinent for the habitat protection of this species.

Keywords: Marbled Murrelets; *Brachyramphus marmoratus*; Breeding distribution; Marine distribution; Modelling Algorithms; Classification and Regression Trees (CART); Artificial Neural Networks (ANNs); Multiple Adaptive Regression Splines (MARS); Generalized Linear Model (GLM)

1. Introduction

The Marbled Murrelet (*Brachyramphus marmoratus*) is an endangered species in North America that has already been studied intensively (for detailed species account see Ralph et al., 1995; Nelson, 1997; Hull, 1999), but its elusiveness leaves significant gaps in many aspects of its biology. Although approximately 45,000–66,000 Marbled Murrelets are [(;l,)-6491 bec [(io34 -1907.(1 0)2166.7akm -1907.((K. -1907.(1(1995)

Table 1

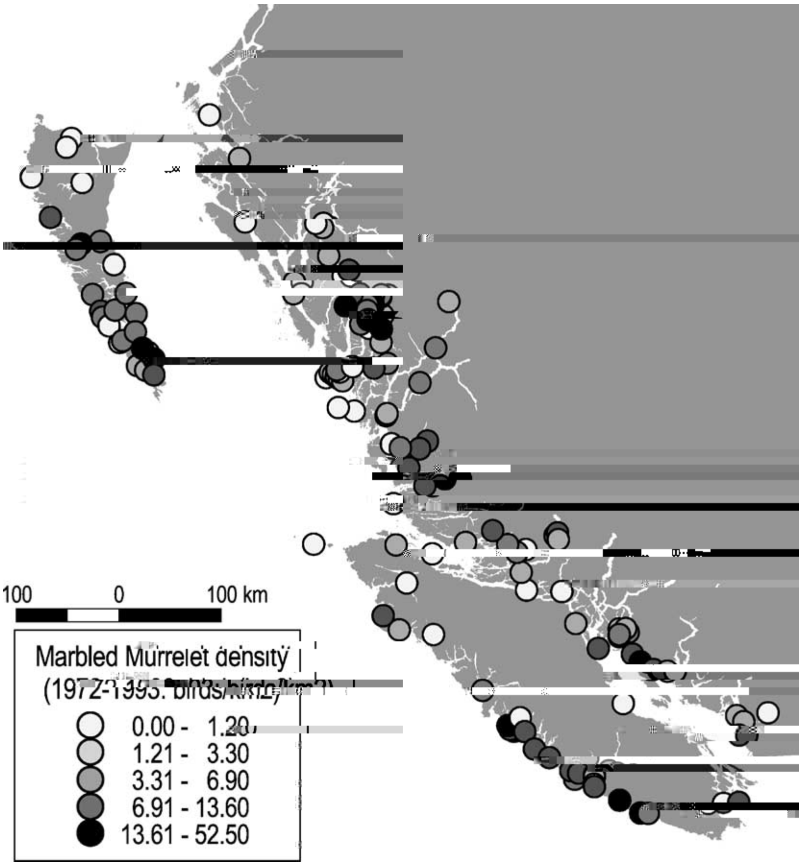

Fig. 1. Map of compiled density data for Marbled Murrelet density (birds/km^2) from 1972 to 1993.

and distribution in British Columbia (density: Fig. 1 and Table 1).

We georeferenced all survey data using BC Geographical Names Information System (http://home.gdbc.gov.bc.ca/) and assembled these in a database (EXCEL and transferred to dBASE); they were displayed with ArcView 3.2 (ESRI, 1996). The count surveys (relative abundance) cover a time period 1922–1989 with the majority of the surveys conducted from late 1960s onwards; the density surveys (absolute abundance) cover a time period 1972–1993. When duplicated surveys at the same location occurred, the averaged survey was used. The two types of surveys, density ($n = 244$ locations surveyed) and counts ($n = 384$ locations surveyed), were generally independent of each other, and each was conducted by different observers. Surveys on ‘confirmed absence’ were seldom collected and occur only in the density data set (as zeros). Confirmed absence differs from survey gaps in that this locale has been investigated and no birds were found. Absences potentially represent regions of low oceanographic productivity with adverse effects on Murrelet survival. Due to the unequal survey effort, counting efforts and differing that such a correlation may exist). For this reason, we regarded the count survey data as too unreliable for analysis and thus excluded from further investigations.

2.2. Abiotic environmental data

We compiled Geographic Information System (GIS) data sets to investigate and describe the productivity of the marine environment within the study area. The environmental features (Table 1) were selected based on existing knowledge of Marbled Murrelets' ecological requirements. All data used apply to the Marbled Murrelet breeding season (April–August; Table 1).

Data on tidal current (cm/s) were generated from a three-dimensional predictive model constructed by Foreman and Henry (1993) and Foreman et al. (1995). This model has been tested in the field, was found to be very reliable and forms the basis for tide table calculations and marine navigation applications (Foreman and Thomson, 1997).

Information on 'sea surface temperature' was obtained from the National Oceanic and Atmospheric Administration (NOAA Coastwatch, 2000) website as point data (for methods see also Huettmann and Diamond, 2001). It consists of monthly long-term temperature averages, with a spatial resolution of a 1° of latitude by 1° of longitude grid cell. The average sea surface temperature from April to August was used to describe the sea temperature of the study area. The point data were smoothed as an interpolated surface by creating a contour using the inverse distance weighted (IDW) method in ArcView.

Fjords that receive glacial run-offs have enhanced marine productivity (e.g. Dunbar, 1973; Shaw, 1989) and thus could attract Murrelets. Glaciers of BC are mapped and available in GIS format from the BC Watershed Atlas (Ministry of Environment Land and Parks, 1999). This GIS data presents known glaciers, as identifiable from satellite images (Fig. 2a).

Estuary locations are also important where river discharge mixes with seawater. This mechanism has been known to increase primary production (Yin et al., 1997), but visibility could be affected for underwater foraging birds. In some cases, the productivity occurs at the frontal zones that form when river and tidal flow are in opposition (Dustan and Pinckney, 1989). Estuary locations are derived from the BC Watershed Atlas: 'Watershed Group Rivers, Lakes, Wetlands and

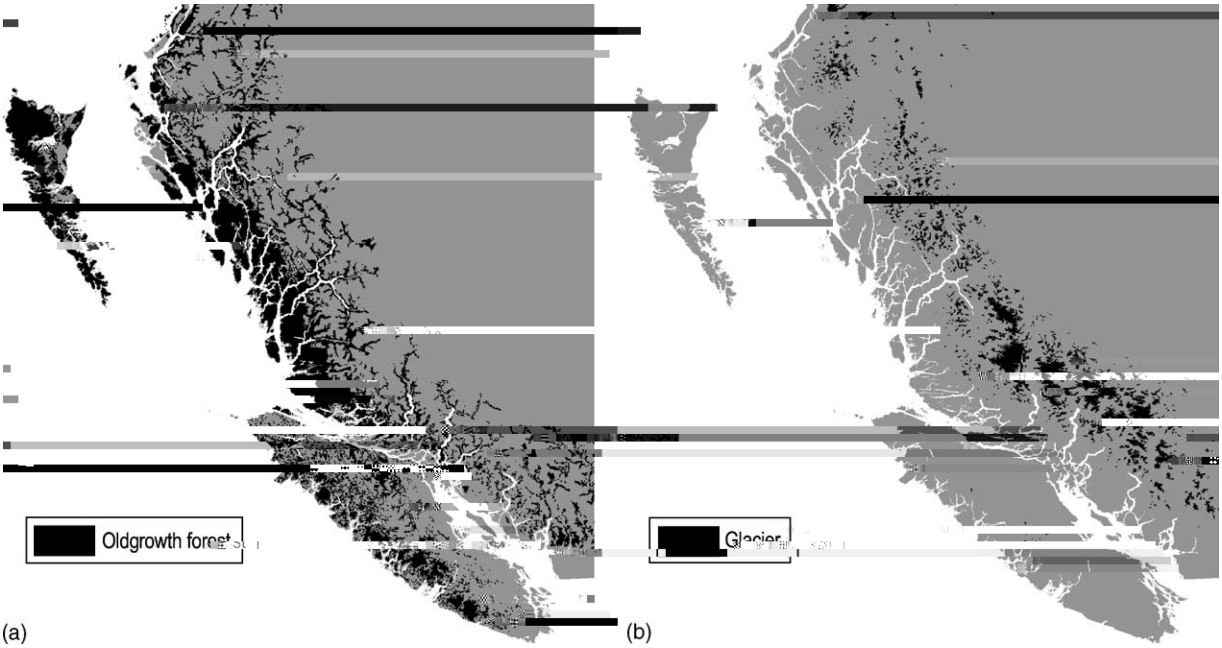

Fig. 2. Maps of (a) known glaciers and (b) known old-growth forest distribution in British Columbia (Inforain, 1998; Ministry of Environment Land and Parks, 1999).

(http://gis.esri.com/arcscripts/). We measured the distance in meters from every point (evenly spaced and surveyed points) to the nearest feature for some environmental themes (glacier, sandy substrate, estuaries), and prey type theme (herring spawn). This was done in ArcView, using the Script 'Nearest Features v. 3', downloadable from the ESRI internet/WWW (http://gis.esri.com/arcscripts/). For the same points, sea surface temperature and tidal current speed overlays were extracted.

2.7. Multivariate model construction

For selecting the model predictors, we used a Generalized Linear Model (GLM), family = Poisson, link = log. In general, we followed the approaches described by Preisler et al. (1997) and Huettmann and Diamond (2001). Poisson distribution was used due to the right-skewed distribution of the density survey data (Preisler et al., 1997). Our parsimonious model included predictors that had a correlation with each other of less than 0.4. We used chi-squared ANOVA (order-dependent) to obtain P-values, and a null model to obtain C_p values (quasi AIC, more or less order-independent) for an alternative evaluation of the predictors (Venables and Ripley, 1994, 2002; Burnham and Anderson, 1999, 2002; StatSci, 2000). The predictor that explained more of the deviance of the pair replaced pairs of predictors correlated above the threshold, 0.4. This method reduces correlation within the model and selects the most predictive variable. Significant predictors for the parsimonious model were also evaluated by AIC allowing for a sound model inference (Burnham and Anderson, 1999, 2002).

In order to fill the gaps on Marbled Murrelet abundance and distribution due to unequal or missing survey efforts, we applied additional modelling algorithms known for their strength of fitting and predictive power for wildlife distribution data (e.g. Verner et al., 1986; Huettmann and Diamond, 2001; Scott et al., 2002). The algorithms used besides GLM (Venables and Ripley, 1994, 2002; Meyer, 1999) are Classification and Regression Tree (CART from Breiman et al., 1984; Bell, 1996; O'Connor and Jones, 1997; Steinberg and Colla, 1997; Salford Systems, 2001), Tree from SPLUS (Venables and Ripley, 1994; StatSci, 2000; Huettmann and Diamond, 2001), Multiple Adaptive Regression Splines (MARS; Friedman, 1991; Steinberg et al., 1999; Salford Systems, 2001), and Artificial Neural Networks (ANNs, Venables and Ripley, 1994; Scardi, 1996; Özesmi and Özesmi, 1999; StatSci, 2000). Except for the GLM, all modelsJ -(Scardi,)-30Feadi, Özesmi, 1999). The errors from the initial classification of the first record is fed back into the network, and used to modify the networks algorithm in the next round, and so on for repeated iterations. The network consists of several layers of neurons, an input layer, hidden layers, and output layers. Input layers take the input and distribute it to the hidden layers (the user cannot see the inputs or outputs for those layers). These hidden layers are required for all necessary computations and transfer the results to the output layer (Hastie et al., 2001). Our ANN model used 0 decay, 4 hidden units, enabled layer skipping and a 'raw' type prediction.

Overall, we followed general default settings of the non-linear algorithms used to allow for algorithm comparisons without special 'tuning'. Our approach using first a GLM for predictor selection followed by non-linear algorithms modelling does not allow for a valid comparison of the importance weighting for predictors across all algorithms; thus, we did not further report this metric.

The predictive models are utilized in two ways. First, they are applied to the habitat features of the evenly spaced points to predict a coastal distribution and abundance of Marbled Murrelets. Next, the models were tested by reapplying each model on the input data for which the Murrelet density is already available (backfitting). The observed abundance was subtracted from the predicted abundance for each survey case. An evaluation of the model performance was based on the distribution of the obtained error. Aside from traditional backfitting, we converted the predicted densities to a percentage of the total sum of predicted density in order to obtain a second, standardized measure of model performance across all predictive algorithms used. Thus, we know the proportion of the total predicted birds and which occur at specific locations. Based on the predicted abundance and distribution of Marbled Murrelets in coastal British Columbia (defined as 1 km offshore), we can extrapolate an estimate of the overall population for BC. Because our model extrapolates densities (birds/km^2) to one location every 10 km interval coastline, we multiplied the predicted densities by 10 to obtain populations within 1 km distance off the coast (see also Hedley, 2000).

To evaluate the findings from the predictions for the marine habitat a posteriori, we applied an external dataset, amount of old-growth forest, to the predictions of even points, and measured the nearest distances. This allows us to explain the remaining 'noise', prediction residuals, from the GLM by the suggested link with Murrelets' known principal terrestrial habitat (Marks et al., 1995; Ralph et al., 1995; Nelson, 1997). This terrestrial dataset plays a considerable role in the overall Murrelet distribution (Ralph et al., 1995). It is not included in the model since the purpose of the model is to determine the effects of marine productivity alone on Murrelet breeding distribution. This approach still allows us to draw a preliminary association between Murrelet's overall habitat requirements (marine and terrestrial).

3. Results

3.1. Compiled surveys

The general Marbled Murrelet abundance and distribution patterns pooled for BC over the years 1930–1996 is shown in Fig. 1. Fig. 3 describes bird abundance and distribution by latitude; Marbled Murrelets were found in abundance along the entire BC coast (density: average (S.D.); 7.24 (6.57) birds/km^2), with major concentrations between 52 and 53°N. However, apparent gaps, particularly on the northern mainland coast, may be attributed to shortage of survey effort rather than lack of birds. We pooled data across years, because we detected no consistent patterns within years. This may be due to averaging affects when working with large geographical scales. In contrast to findings by Burger (1999), we detected no El Nino year effects, and conclude that eitherResult12.p

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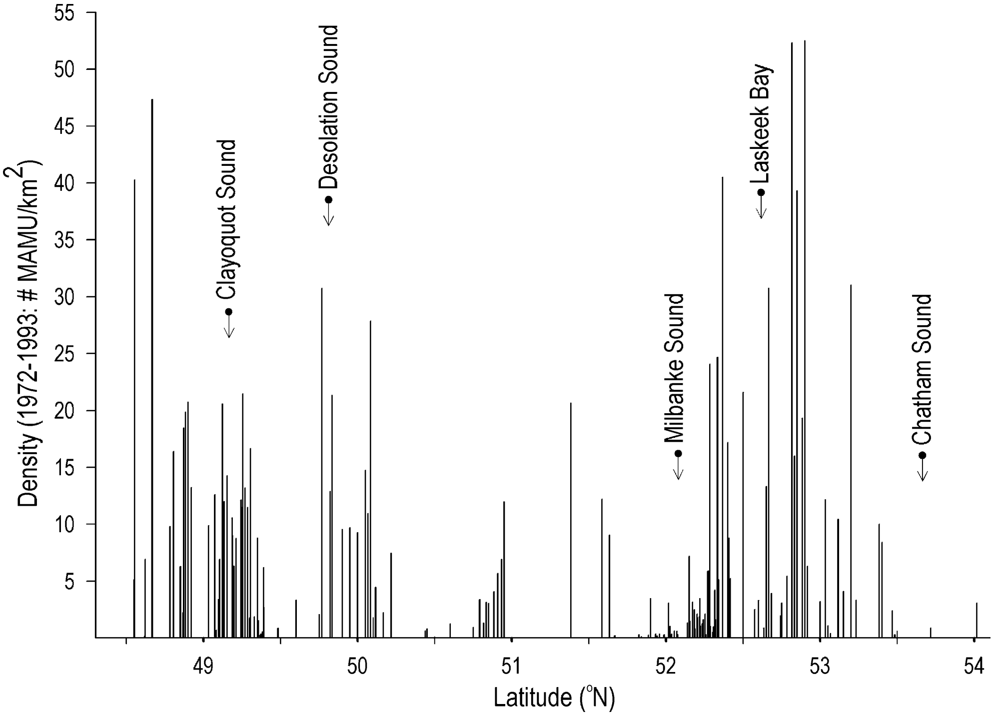

Fig. 3. Count and density surveys pooled over all years by North Latitude.

model predictions by being less parsimonious since it allows for higher correlation among the predictors (non-parsimonious model). However, using this type of model did not improve the amount of residual deviance explained 1965 (best-fit) versus 1966 (parsimonious) of an overall 2315 residual deviance (Table 2). Therefore, this approach was not further pursued. The parsimonious GLM is used to allow for the best inference on the determination of Marbled Murrelet ma-

Table 2
Significant predictors in the parsimonious GLM of the density surveys used in the BC coast model ($n = 244$)

Predictors	P-value	C_p	Intercept	Coefficient
Estuary	<0.0001	2969	-0.09	

Table 3
British Columbia population estimates (maximum marine carrying capacity) from density models and rounded off to the nearest thousands

	GLM	CART	Tree	MARS	ANNs
Estimated population	176000	179000	170500	183700	164000

All values corrected for backfitting errors.

Table 4
Model evaluation based on the summary of backfitting results from

8.8). The Tree-SPLUS algorithm also better predicted the real density than all other algorithms with a S.D. of 2.9 (Table 4).

Fig. 5 compares the relative algorithm outputs of the predictions. The magnitude of percent of predicted output is expected to be similar across algorithms used. Although Fig. 5 shows that this is not always

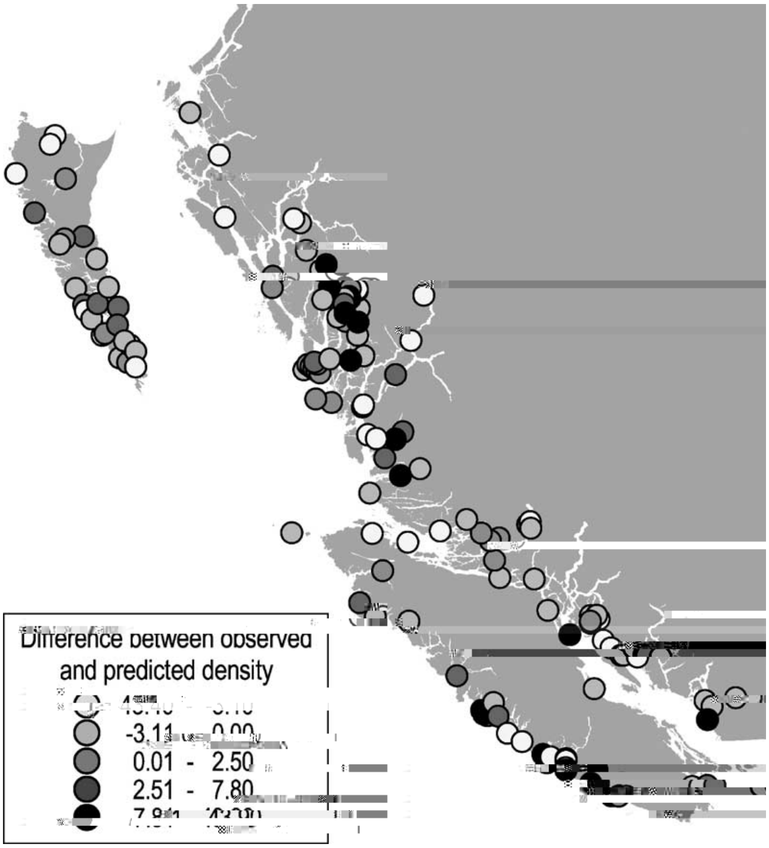

Fig. 4. The difference in estimates between the observed density and the density predicted by the tree algorithm. The classification is divided into five quantiles.

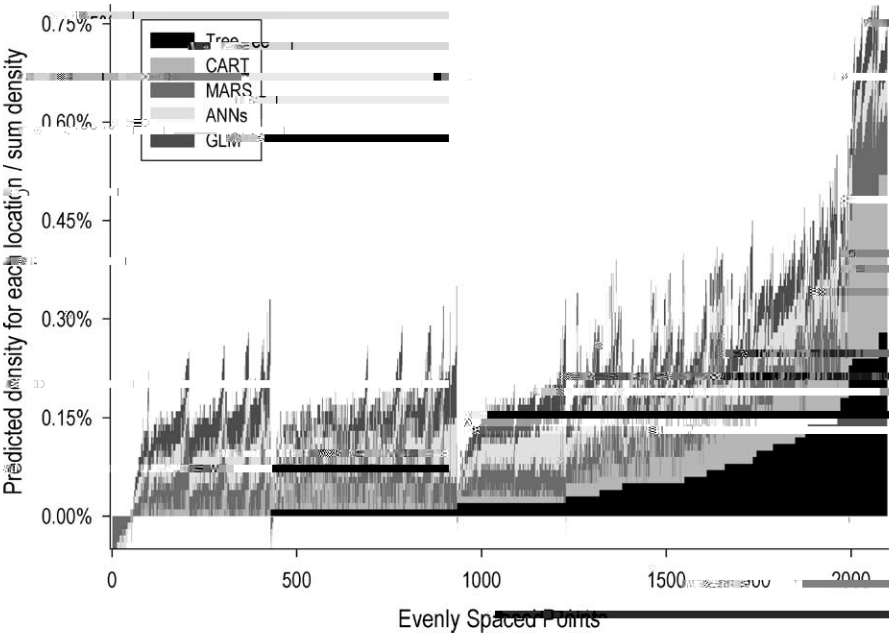

Fig. 5. A visual comparison of all model behaviours at the same locations. Each percent represents individual predictions divided by the sum of the predicted densities across all modelling algorithms used.

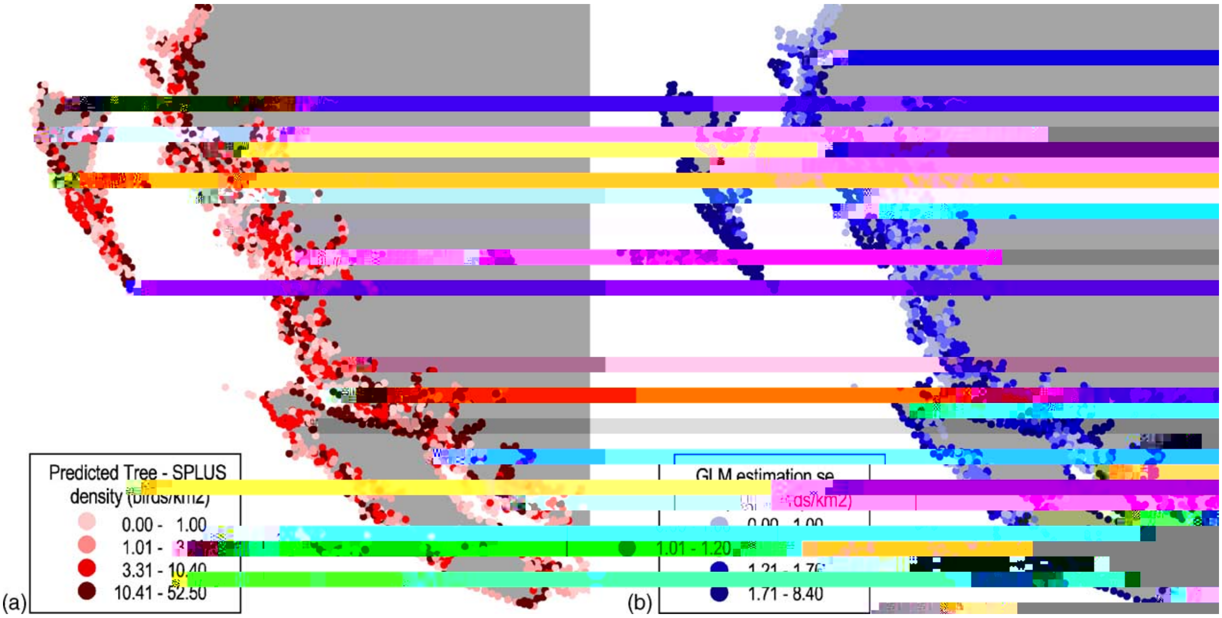

Fig. 6. (a) Predictive Tree model output for Marbled Murrelet densities along the BC coast. (b) The distribution of GLM standard error.

3.4. Predictive map and predicted population estimates

Fig. 6a is based on the classification and regression tree (Tree from SPLUS) model identified as the best model based on criteria used. Besides predictions, we also show the related standard error of the GLM with the selected predictors (Fig. 6b). Doing so allows for evaluation of the spatial prediction accuracy for individual locations. For the predicted density model, the areas Southern and North Eastern Queen Charlotte Island, Discovery Passage, Southern Vancouver Island, the fjords of Central Coast, Southern and Western Vancouver Island and the fjords of Strait of Georgia showed higher abundances. Predicted densities are low north of Queen Charlotte Island, Northern coastal British Columbia, Northern Vancouver Island and Southwest of Vancouver Island.

effort, this could have far-reaching effects for Murrelets and other seabirds that rely on herring as a food source. Little has been done to quantify the effects, if any, of commercial herring harvesting on Murrelets' abundance and reproductive success.

Recently, there has been an increasing awareness of nearshore developments, such as 'log booming' activities, and mariculture establishments which could affect water quality (Hay and McCarter, 1999) and the spawning sites of herring. In addition, the large-scale impacts of oil spills, fisheries and ocean climate changes on herring spawn distribution should also be considered as detrimental to Murrelet populations.

4.4. Glaciers and estuaries

Glaciers and estuaries have certain features in common. They both result in an influx of fresh water and both lead to mixing of water bodies, yet estuaries are positively correlated with Murrelet density, whereas glaciers are negatively correlated.

We found that Murrelets tend to be found further from glaciers. This provides a new aspect of stratifying the marine environment relevant to Marbled Murrelets. The further the distance from glaciers, the less likely Marbled Murrelets will encounter run-off formed by glacial meltwater (Dunbar, 1973; Matthews and Quinlan, 1975).

Estuaries are unique aquatic environments that have an additional source of buoyancy input derived from freshwater inflow, and an additional source of mechanical energy from tidal stirring. As a consequence of a combination of estuary surroundings without glacial meltwater, distinct bloom dynamics can be established that are different from those observed in lakes and open oceans (see also Cloern, 1991).

The mechanics of this mixing are initiated when the discharged water mixes with the saltwater, and plume fronts often form. This mixing may take place in an estuary, or directly in the open ocean where the estuary itself discharges into the coastal sea. Due to differences in salinity and temperature, a distinct front of a more detailed distribution scenario for Marbled Murrelets is needed (e.g. finer spatial and temporal stratification).

tire Pacific. The establishment of centralized and high quality databases for Marbled Murrelets and their marine and terrestrial habitats are crucial concepts to assure effective conservation for this species of international concern.

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