Estimating 30-year Change in Available Coastal Old-Growth Habitat for a Forest-nesting Seabird (*Brachyramphus marmoratus)* in British Columbia, Canada

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Abstract

The marbled murrelet, *Brachyramphus marmoratus*, is an old-growth dependent species that nests in North American coastal forests. Canadian population and occurrence data are limited; however, concern over loss of nesting habitat in coastal British Columbia led to a conservation assessment of *Threatened* by the Committee on the Status of Endangered Wildlife in Canada, and subsequent listing under the Canadian *Species at Risk Act*. Information on the availability and patterns of change in nesting habitat is essential for making land use decisions and for monitoring the conservation status of this wide-ranging seabird. We estimate potential marbled murrelet nesting habitat for the coast of British Columbia at two points in time, 1978 and 2008, and quantify habitat loss and modeled habitat recruitment over this 30 year time period, a key time frame for the assessment of the conservation status of this high-profile species. We used the recommendations from the Canadian Marbled Murrelet Recovery Team and forest cover attributes to perform province-wide implementation of three predictive habitat suitability models, ranging from exclusive to more inclusive models. Based on the various habitat model scenarios, including corrections using aspatial harvest records, we estimate that 20 to 24% of potential marbled murrelet nesting habitat has been lost to forest harvest and fire from 1978 to 2008. If modeled habitat recruitment is considered, then net change in potential nesting habitat is 20 to 22% loss. Our estimates of potential murrelet habitat and subsequent habitat loss and change are influenced by numerous sources of uncertainty, such as actual suitability of forest stands for breeding murrelets and known deficiencies in the forest harvest spatial datasets. However, the results presented here provide the first

range of province-wide habitat change possibilities and are consistent with previous regional analyses of potential marbled murrelet habitat loss in British Columbia.

Key Words: Marbled Murrelet, Nesting Habitat, Spatial Modeling, Habitat Loss, British Columbia, Geographic Information Systems, GIS

INTRODUCTION

Marbled murrelets (*Brachyramphus marmoratus*) are small seabirds that live along the northern Pacific coast of North America. Unlike typical members of the alcidae family, marbled murrelets nest primarily in the trees of coastal old-growth forests (Burger 2002, Piatt et al. 2007). The distribution of marbled murrelet ranges from northern California to Alaska, with larger murrelet populations found at higher latitudes and the majority of the global population found in Alaska (Piatt et al. 2007). It is estimated that British Columbia, the sole range of breeding marbled murrelets in Canada, is home to approximately 99,600 marbled murrelets (72,600–125,600, Bertram et al. 2007). Details of the spatial distribution of the murrelet population within British Columbia are limited; marine environments have not been systematically surveyed across the province (but see Yen et al. 2004), and their cryptic nesting behaviour makes them difficult to study, especially in remote terrestrial locations (CMMRT 2003). While marine surveys, along with historical anecdotes of abundance, have suggested a sharp decline in marbled murrelet populations in some areas, other data suggest some stable populations in British Columbia (e.g., Kelson et al. 1995, Burger 2002, Lank et al. 2003, Piatt et al. 2007). However, historical information on the number of marbled murrelets in British Columbia and population or demographic data are limited for this elusive species (CMMRT 2003).

The Canadian population of marbled murrelets was assessed as *Threatened* by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2000), resulting in the legal listing of the marbled murrelet under the Canadian *Species at Risk Act* (SARA). With limited information on population status (e.g., decline of mature individuals), the Canadian marbled murrelet conservation assessment was based on an estimated reduction in the extent of old-growth forest nesting habitat in coastal British Columbia over approximately 30 years, or three generations, a standardized time window for species conservation assessments (IUCN 2010, COSEWIC 2000). Loss of terrestrial nesting habitat is considered the primary threat to marbled murrelet populations range-wide (CMMRT 2003, Piatt et al. 2007) and is well supported by the literature (e.g., Burger 2001, Burger 2002, Raphael et al. 2002, Piatt et al. 2007, Burger & Waterhouse 2009). Other threats to population persistence occur in the marine environment, including fisheries by-catch and oil spills (CMMRT 2003). In addition, recent research has highlighted the potential role of historical depletion of food supply (i.e., fisheries) in marbled murrelet declines and/or the potential for population recovery (e.g., Becker & Beissinger 2006, Becker et al. 2007, Beissinger & Peery 2007, Norris et al. 2007, Gutowsky et al. 2009).

Marbled murrelet nesting habitat has been well characterized at landscape, stand, tree, and platform levels (e.g., Burger 2002, Piatt et al. 2007, Burger et al. 2010). Marbled murrelet nests are typically found in trees with large branches and sufficient epiphytic growth (e.g., Burger et al. 2010), characteristics that are usually found in relatively older and taller trees (e.g., > 250 years, > 28.5 m high, Burger 2002). Associations of nest sites with other macro-habitat features, such as elevation and distance-to-sea, have also been investigated in order to characterize suitable habitat over increasing scales (Burger 2002). Nest trees are generally found up to 50 km inland, but mostly within 30 km from the shoreline (Burger 2002), as these seabirds are limited by the commuting distance from foraging areas (Hull et al. 2001).

Quantifying the degree of change in available marbled murrelet old-growth nesting habitat through time is necessary for characterizing present and predicting future abundance of marbled murrelets in British Columbia, assuming that terrestrial habitat is a key predictor of population abundance and an indicator of the likelihood of local population persistence (e.g., Burger 2001, Steventon et al. 2003, Burger & Waterhouse 2009). Recent research efforts have produced regional- and broad-scale estimates of potential murrelet nesting habitat for single time periods (e.g., Waterhouse et al. 2008, Waterhouse et al. 2009, Mather et al. 2010), as well as a few unpublished regional-scale or shorter time-frame analyses estimating change in available murrelet habitat (e.g., Tomlins & Gray 2007, Gowgaia Institute 2007).

In this study we used Geographic Information Systems (GIS) and habitat suitability modeling techniques to implement a set of three spatially explicit, province-wide terrestrial marbled murrelet habitat models. As well, we estimated the amount of forest disturbance, from forest harvest and fires, and resulting change in availability of predicted marbled murrelet nesting habitat over a 30-year period for the entire coast of British Columbia. We mapped forest conditions in two time periods, 1978 and 2008; applied three predictive marbled murrelet nesting habitat suitability models to estimate the amount of nesting habitat available for the years 1978 and 2008; quantified the amount of loss from forest harvest and fire; and finally, calculated net change, assuming modeled recruitment of suitable nesting habitat between 1978 and 2008. The results presented here provide the first province-wide account of spatially explicit habitat change scenarios, and we discuss the benefits and limitations of a spatially explicit approach for deriving estimates of species habitat change over large areas.

METHODS

Study area

The study area includes the entire coast of British Columbia, the current range of the breeding population of marbled murrelets in Canada (CMMRT 2003). The study area is divided into six conservation regions of different sizes: West and North Vancouver Island (2.15 million ha); East Vancouver Island (1.15 million ha); Southern Mainland Coast (3.97 million ha); Central Mainland Coast (4.21 million ha); Northern Mainland Coast (5.61 million ha); and Haida Gwaii (1 million ha) (Figure 1). These regions were developed by the Canadian Marbled Murrelet Recovery Team (CMMRT), and are based on forest districts, land and wildlife management regions, and ecosection boundaries (CMMRT 2003). Each conservation region differs in the current estimated abundance of marbled murrelets and in conservation priorities (CMMRT 2003).

Marbled murrelet nesting habitat model selection

Several predictive attributes and models of potentially suitable marbled murrelet nesting habitat have been developed for British Columbia (e.g., McLennan et al. 2000, Bahn & Newsom 2002, CMMRT 2003, Chatwin & Mather 2007, Mather et al. 2010). All predictive habitat models carry some degree of uncertainty, due, for example, to limited or poor quality input data (e.g., Waterhouse et al. 2010). In an attempt to account for the influence of model uncertainty, we implemented three predictive marbled murrelet habitat suitability models. The three models reflect a range of predictive scenarios of potential marbled murrelet nesting habitat from an exclusive model (Model 1; CMMRT 2003), an intermediate model (Model 2; Mather et al. 2010), to an inclusive model

(Model 3; CMMRT 2003). All three models use four key environmental variables (forest height, forest age, elevation, and distance from nearest ocean shoreline; Table 1), which are appropriate for large area modeling of potential marbled murrelet nesting habitat.

Model 1, based on guidelines developed by the CMMRT (CMMRT 2003), uses the most exclusive definition of potential marbled murrelet nesting habitat. Model 1 is equivalent to the CMMRT's estimate of "most likely" habitat (see Table 1), where habitat is considered potential marbled murrelet nesting habitat if forest age is ≥ 250 years, forest height is ≥ 28.5 m, and location is 500 m to 30 km from ocean shorelines. Elevation thresholds varied from ≤ 500 m to ≤ 900 m and depend on conservation region (Table 1). Model 1 indicates potential habitats considered most likely to provide suitable nesting habitat for marbled murrelets in British Columbia (CMMRT 2003).

Model 2 is the most common set of parameters used for estimating potential marbled murrelet nesting habitat in coastal British Columbia (Chatwin & Mather 2007, Mather et al. 2010, Waterhouse et al. 2010). Model 2 uses the attribute thresholds from Mather et al. (2010), which are based on a hybrid of the CMMRT's predicted "most and moderately likely" guidelines for habitat attributes (CMMRT 2003). In this case, nesting habitat is modeled as locations with forests aged ≥ 140 years, heights ≥ 28.5 m, and distance to ocean shoreline between 0 and 50 km. Elevation classes associated with Model 2 are the same as with Model 1.

Model 3 employs the most inclusive definition of potential marbled murrelet nesting habitat, with a location considered potential marbled murrelet nesting habitat if it met the requirements of the CMMRT's model for either "most likely" or "moderately likely" habitat (Table 1). Forest age is ≥ 140 years, forest height is ≥ 19.5 m, and location is 0 to 50 km from ocean shorelines. Elevation thresholds in Model 3 are higher than other models and range from ≤ 800 m to ≤ 1500m depending on conservation region (Table 1). Given the inclusivity of this parameter set, the recovery team recommended detailed ground-truthing of “moderately likely” habitats to ensure that these habitats contain the potential attributes required for nesting marbled murrelets (CMMRT 2003).

Data Sources

The distance-to-ocean-shoreline variable was computed using British Columbia’s Baseline Thematic Mapping (BTM) data (British Columbia Ministry of Environment, Lands and Parks 1995). This dataset was derived using visual interpretation of Landsat satellite imagery from the early and mid 1990s and provides a coarse definition of British Columbia land cover and coastline. Included in this dataset is a saltwater map, from which distance-to-ocean-shoreline calculations were made. Using the BTM data, deep inlets, which occur regularly along the coast of British Columbia, are considered saltwater and were used in distance-to-ocean-shoreline calculations.

Elevation was determined using a digital elevation model (DEM), with a spatial resolution of 25 m. This DEM was created from 1:20 000 Terrain Research Information Management data (Province of British Columbia, 1996) and is reported to be accurate within 10 m (British Columbia Ministry of Sustainable Resource Management 2002).

In British Columbia, the most complete dataset for mapping forest age and height variables is the forest inventory, which contains detailed age and height information on forest stands, is spatially continuous, and covers 90% of our study area. Regions excluded from the forest inventory data include privately owned timber land holdings, such as those along the southeast coast of Vancouver Island, as well as some park lands. Polygons, the spatial unit of the forest inventory, are used to represent forest stands (Leckie & Gillis 1995) and are commonly selected as the spatial unit for modeling marbled murrelet habitat over broad spatial scales (e.g., Chatwin & Mather 2007, Mather et al. 2010). In constructing the forest inventory, forest stand attributes were visually interpreted from aerial photographs. Stand age is the average age, in years, of the dominant and co-dominant trees in a forest stand and is typically estimated indirectly from aerial photographs. Stand ages are recorded as individual years, but also grouped into categories: 1–20 years, 21–40 years, 41–60 years, 61–80 years, 81–100 years, 101–120 years, 121–140 years, 141–250 years, and > 250 years. Interpretation of individual stand age becomes increasingly difficult as forests reach maturity; as such, category midpoints are often assigned as the forest age for the individual year attribute (Wong et al. 2003). We used individual stand age in our analysis. Stand height is interpreted directly from the aerial photograph and reported in metres.

For the remaining 10% of the study area, where forest inventory data are unavailable, BTM data (British Columbia Ministry of Environment, Lands and Parks 1995) was used. BTM data provides broad information on stand age, reported as age categories: old forest (> 140 years), young forest (20–140 years), and recently harvested (< 20 years). Height variables are unavailable with the BTM data, but it was assumed old forest stands were also of suitable height for marbled murrelet nesting habitat.

Sources of change to potential marbled murrelet nesting habitat

Since the goal is to estimate change in potential marbled murrelet habitat between 1978 and 2008 we required data for each environmental variable at each time period. Distance to ocean shoreline and elevation do not change between time periods. As forest stands age, height growth slows, reaching a constant once mature (Ryan & Yoder 1997). Given the broad height classes used in marbled murrelet habitat modeling, height changes have little impact on model estimates and therefore were treated as static in the analysis. Forest stand ages were modeled dynamically, changing stand age appropriately from 1978 to 2008.

Forest disturbances, including those from both anthropogenic (e.g., harvest) and natural (e.g., fire) causes, represent the primary sources of loss to potential marbled murrelet nesting habitat (CMMRT 2003). The forest inventory and BTM datasets have not been judiciously updated and are missing many forest disturbances from 1978 to 2008. Thus, it was necessary to look to other data sources to obtain complete forest disturbance records. Spatially explicit forest disturbance data are available from a variety of data sources (see Table 2). Due to known deficiencies (both spatial and temporal) we complemented the available forest disturbance data with a Landsat-based change detection method using the enhanced wetness difference index (EWDI). The EWDI is based on the wetness component of the tasselled cap transformation and can be used to spatially identify large forest disturbances (Franklin et al. 2001, 2002). We restricted our analysis to those disturbances > 1 ha to align with existing disturbance datasets (Ann Morrison, British Columbia Ministry of Forests and Range, Forest Analysis and Inventory Branch, pers. comm., 2009). All forest disturbance data (see Table 2) were combined to create a single, spatially explicit forest disturbance dataset for 1978–2008.

Landsat imagery is unavailable prior to 1985 and thus our method using Landsat imagery to fill in gaps cannot be used from 1978–1985. Alternatively, we draw upon aspatial harvest records for 1978–1985 to improve our calculation of forest disturbance and subsequent estimates of potential marbled murrelet nesting habitat loss.

Estimating change in modeled nesting habitat

We combined the forest inventory data with forest disturbance data using appropriate GIS operations (Figure 2) to derive forest attribute datasets for 1978 and 2008. Forest attribute data for 1978 and 2008 are combined with distance-to-ocean-shoreline and elevation data to implement the three marbled murrelet nesting habitat models (Figure 2).

When forest age is included in a habitat model, there are two approaches to modeling habitat loss. Habitat loss can be modeled as the amount of habitat observed in the initial time period (1978) minus the amount of habitat lost between the first and second time periods (1978 and 2008). This approach does not consider increases to forest age and ignores the opportunity for new habitat to be recruited into potentially available classes over the study time period, in this case 30 years. For instance, suitable habitat that was too young in 1978 crosses the model age threshold in 2008. In this example, recruitment of habitat is controversial as it represents the creation of new ‘old-growth’ forest. However, consideration of habitat recruitment is important as it preserves equivalent definitions of potential marbled murrelet habitat—from a data perspective—at both time points. We considered both types of analyses: habitat loss and net change in habitat, the latter including modeled habitat recruitment.

RESULTS

Marbled murrelet nesting habitat models

The predictive habitat models we implemented suggest that the spatial extent of potential marbled murrelet nesting habitat in 1978 covered 1.36 million to 4.70 million ha, depending on the model (Figure 1, Table 3). The regional estimates of predicted marbled murrelet nesting habitat varied by model, with either the West and North Vancouver Island Region or Central Coast Region containing the largest amount of predicted nesting habitat (Table 3). The spatial extent of predicted marbled murrelet nesting habitat in 2008 ranged from 1.29 million ha to 4.03 million ha, with the intermediate Model 2 predicting 2.1 million ha of available marbled murrelet nesting habitat in 2008 (Figure 1, Table 3).

Marbled murrelet nesting habitat model loss

We spatially detected a total of 1.06 million ha of forest disturbance (from harvest and fire) within the study area from 1978 to 2008 (Figure 1). Forest fires accounted for less than 5% of all disturbance area, occurring primarily at substantial distances from the ocean shoreline, making fire a relatively minor disturbance factor in this analysis. By area, 26% of all disturbances intersected Model 1 habitat in 1978, 50% intersected Model 2 habitat, and 73% intersected Model 3 habitat (Figure 1, Table 3; Loss column). Our estimates of marbled murrelet nesting habitat loss ranged from 16.3% to 20.6%, (Figure 1, Table 3). Models 1 and 2 showed very similar percentages of overall habitat loss, 20.2% and 20.6%, respectively. Regionally, percent habitat loss using each of the three models was also similar, except for East Vancouver Island (16.8 to 27.1%) and the South Coast (17.4 to 27.6%; Table 3). Generally, estimated habitat loss was highest in West and North Vancouver Island Conservation Regions, regardless of the model (25.6 to 27.9%). Predicted amounts of habitat loss were also high in South Coast (17.4 to 27.6%) and East Vancouver Island Conservation Regions (16.8 to 27.1%), depending on the habitat model (Table 3).

Marbled murrelet nesting habitat model recruitment

Modeled habitat recruitment, based on forest aging over 30 years, had a varied impact on model outputs (Figure 1, Table 3; Recruitment column). Models 2 and 3, both with thresholds for potentially suitable nesting habitat using ≥ 140 year forest age, had relatively similar estimates of modeled habitat recruitment, with ~2% of the 2008 predicted available habitat resulting from modeled recruitment (52,582 ha and 91,262 ha, respectively; Table 3). Model 1, which was the most exclusive estimate of potential habitat with a forest age threshold for nesting habitat of ≥ 250 years, had the most recruitment with ~15% of the 2008 potential habitat resulting from recruitment (201,067 ha; Table 3). Regionally, Model 2 and Model 3 had different overall amounts of recruitment, but similar general patterns. For example, the most (South Coast) and least (East Vancouver Island) amount of modeled habitat recruitment were the same for both models (Table 3).

Marbled murrelet nesting habitat model change

Provincially, the percentage change in potential marbled murrelet nesting habitat, considering both habitat loss from harvest and fire and modeled habitat recruitment, varied from -5.4% to -18.5% depending on the model (Table 3; % Change column). Model 1, which had the most recruitment, showed the smallest amount of change (-5.4%); Model 2 showed the most change (-18.5%); Model 3 showed moderate change at -14.4% (Table 3). Again, regional trends associated with change were variable across models. According to Model 1, the South Coast has had the greatest net loss in potential marbled murrelet nesting habitat (-18.0%). For Models 2 and 3, net loss was greatest in West and North Vancouver Island (-26.9% and -25.8%) followed by East Vancouver Island (-26.5% and -24.0%; Table 3).

DISCUSSION

We used GIS and habitat suitability modeling to derive estimates of potential marbled murrelet habitat, habitat loss due to harvest and fire, and net change of potential marbled murrelet habitat from 1978 to 2008, which included estimates of habitat recruitment.

Our modeled 2008 estimates of potentially suitable habitat for nesting marbled murrelets in British Columbia were similar to other range-wide binary habitat suitability studies (e.g., Mather et al. 2010). In particular, our estimate of overall 2008 Model 2 potential nesting habitat (2,109,938 ha) was very close to an estimate from an earlier modeling study that used the same parameter set, but some different data sources and methods (1,980,846 ha; Mather et al. 2010). The minor differences in the two estimates are most likely due to sources of data; for example, our study utilized Landsat-based change data for most of the coast to estimate disturbance as opposed to forest inventory data (Mather et al. 2010). However, the ~6% difference in the two potential habitat availability estimates were largely due to different estimates for the Haida Gwaii and West and North Vancouver Island Conservation Regions, with our predicted estimates much higher for these regions (this paper, Mather et al. 2010). These differences may result from specific variations in model implementation for these two regions, as Mather et al. (2010) substituted their coast-wide algorithm with a local model in the Clayoquot Sound area of West Vancouver Island (Bahn & Newsom 2002) and aerial photo interpretation data in Haida Gwaii (Waterhouse et al. 2009, Burger et al. 2009, Waterhouse et al. 2010).

Forest disturbances had the largest impact on Model 2 potential habitat (20.6% loss). Considering the coast-wide scale of the analysis, the estimates of habitat loss were relatively similar across all three models. However, estimates of modeled habitat recruitment, and resulting net change in available habitat, varied considerably among models (Table 3). The high level of estimated habitat recruitment in Model 1 is most likely an artefact of the limitations of the forest inventory data (Waterhouse et al. 2010), in conjunction with the most exclusive definition of potentially suitable nesting habitat (CMMRT 2003). In mature forests, age class midpoints were frequently adopted due to difficulty interpreting exact ages, leading to clustering in the forest age class frequency distribution (Wong et al. 2003). The high levels of recruitment in Model 1 are likely an artefact of an age class cluster going from <250 years in 1978 to ≥250 years in 2008, as opposed to an actual estimate of biologically meaningful nesting habitat recruitment (CMMRT 2003). In general, any estimate of recruitment of potential marbled murrelet nesting habitat over relatively short time scales (e.g., 30 years) should be considered with caution, as the attributes that 'recruit' through time (e.g., forest age) are simply surrogates based on limited datasets (Waterhouse et al. 2010). In the case of potential marbled murrelet nesting habitat, it is unlikely that the platform characteristics associated with older forests necessary for marbled murrelet nesting, such as moss-covered branches, 'recruit' within relatively short time frames (CMMRT 2003, Burger et al. 2010). However, this same 'caution' should be applied to single time-frame habitat models, such as our 1978 models. In this case habitat was deemed suitable by forest stand age or height class; however, some of the identified stands are unlikely to contain the necessary platform characteristics (e.g., forest stand age 251 years). Thus, excluding considerations of 'recruitment' habitat in the latter time span of change analyses only could lead to a biased interpretation of habitat loss or change.

Our detection of forest disturbances, from harvest and fires, were limited by available spatial data sets. For example, our forest disturbance data captures only clear-cut type harvesting. Other harvesting practices, such as partial-retention harvesting, can similarly impact potential murrelet nesting habitat. However, throughout our study area the amount of partial-retention type harvesting is inconsequential when compared to the level of clear-cut harvest (British Columbia Ministry of Forests and Range 2010). Forest harvests of < 1 ha were not captured within two of the forest disturbance change layers (our Landsat-based, and CDL, Table 2).Complete spatial harvest data for 1978 to 1985 was also lacking (see Methods). To investigate the effect of limited spatial data from 1978 to 1985, we can compare our spatial forest disturbance data with aspatial harvest reporting records in the Ministry of Forests and Range's Annual Reports (British

Columbia Ministry of Forests 1979–1986). Our spatial estimates of forest disturbance from 1985–2008 (where our data are most complete) align well with documented aspatial harvesting records, suggesting our disturbance layer is relatively robust and that the missing <1 ha disturbances may be negligible relative to the scale of this analysis.

Given the known deficiency in our data from 1978 to 1985, an option for mitigating this effect is to supplement our estimates using aspatial harvest information from the annual reports. For example, the total amount of harvest over our study area from 1978 to 1985, according to the annual reports, was approximately 366,000 ha of harvest. This number was generated by adding harvest records from the Vancouver Forest Region and the Prince Rupert Forest Region, with totals for the Prince Rupert Forest Region scaled by 0.44 to reflect the proportion of our study area that fell within this forest region and assumes no spatial bias of harvests in this region. Using the spatial forest harvest data for 1978 to 1985 (see Table 2), 176,000 ha of harvest were spatially detected during this time period and thus already considered in our spatial analyses. Therefore, an additional 190,000 ha of forest loss due to harvest occurred from 1978 to 1985 that we did not detect due to limited spatial data over this time frame. If we assume the same disturbance proportions for the 190,000 ha forest disturbances within each habitat model as other disturbances (Model 1 – 26%, Model 2 – 50%, Model 3 – 73%; see Results), then our adjusted estimates of potential nesting habitat loss would be 19% to 24% depending on model, or -9% to -22% net change in potential nesting habitat if modeled recruitment is considered. These adjusted estimates are likely closer to the actual degree of potential marbled murrelet nesting habitat loss, although this type of aspatial adjustment includes numerous assumptions.

Our results are based on a set of potential marbled murrelet nesting habitat models, ranging from exclusive to inclusive definitions of potential nesting habitat; however, all three models applied are appropriate for broad-scale and strategic planning (e.g., Burger et al. 2005, Mather et al. 2010, Waterhouse et al. 2010). Model 2, which is based on the Mather et al.'s (2010) intermediate parameter set, performed well in the North Coast Conservation Region when tested against low-level aerial habitat surveys, with 99% of sites (84/85) modeled as habitat containing some marbled murrelet habitat attributes (Burger et al. 2005). However, Model 2 was found to underestimate habitat suitability when compared to aerial photo assessment methods in other regions of the coast (Waterhouse et al. 2010). The Mather et al. (2010) model has been selected by the CMMRT as the baseline for monitoring the relative abundance of potential marbled murrelet nesting habitat in British Columbia through time.

Our 30-year, province-wide spatial analyses and corrected estimates of potential marbled murrelet habitat loss, based on Model 2 (20.6% and 24%, respectively) and Model 3 (16.3% and 20%, respectively), were similar to values reported in previous regional or shorter time-frame analyses of marbled murrelet nesting habitat change in British Columbia. The British Columbia Ministry of Forests estimated that approximately 24% of potential marbled murrelet nesting habitat had been harvested from 1973 to 2000, based on BTM data (Marvin Eng, British Columbia Forest Practices Board, pers. comm., 2009). Tomlins and Gray (2007) reported an 18.3% loss of potential marbled murrelet nesting habitat from 1985 to 2005 in the Sunshine Coast Forest District of British Columbia, with a 12% net loss, when offsetting for recruitment of nesting habitat over the same time period is considered. Finally, the Gowgaia Institute (2007) estimated that

92,776 ha (31,474 ha from 1978 to 1985; 61,302 ha from 1985–2008) of forests were logged on Haida Gwaii from 1978 to 2008, based on their high spatial-temporal resolution harvest dataset for the region. Our spatial analysis revealed forest disturbance for Haida Gwaii covering 67,203 ha (9,183 ha from 1978 to 1985; 58,020 ha from 1985–2008). While our forest disturbance data underestimates disturbance area when compared to high resolution imagery, the majority of the underestimation occurred expectedly between 1978 and 1985, due to missing spatial harvest records. However, we adjusted for the missing spatial data coast-wide by using an aspatial estimate of additional forest disturbance from 1978 and 1985. Our adjusted coast-wide estimate is likely more robust, regardless of model choice.

Our estimates of potential murrelet habitat and subsequent habitat loss and change are influenced by uncertainty (e.g., upward or downward biases), such as actual suitability of forest stands for breeding murrelets (e.g., presence of suitable limbs for nesting) and known deficiencies in the forest harvest spatial datasets. In our study, Models 2 and 3 produced similar estimates of potential nesting habitat loss and change and we feel that these two models and associated analyses provide a realistic range of potential habitat loss and net change scenarios in British Columbia over the past 30 years. These results provide the first province-wide habitat change scenarios and are consistent with previous regional analyses of potential marbled murrelet habitat loss in British Columbia.

CONCLUSIONS

Based on our intermediate and inclusive habitat models, with the aspatial adjustment included, we estimate that 20 to 24% of potential marbled murrelet nesting habitat has been lost to forest harvest and fire from 1978 to 2008. If modeled recruitment is considered, then net change in potential nesting habitat would be 20 to 22% loss. The potential marbled murrelet nesting habitat models and our resulting disturbance and change estimates presented here are intended to support strategic land use decisions and monitoring the status of this wide ranging species (CMMRT 2003, Steventon et al. 2003, Burger & Waterhouse 2009, Waterhouse et al. 2010). Given the paucity of data on population trends of marbled murrelets in British Columbia, these 30-year changes in terrestrial habitat data are particularly informative for re-occurring assessments of the conservation status of this high-profile species in Canada (COSEWIC 2000).

Broad and regional scale modeling of habitat is important for management and provides an approach for monitoring wildlife when population and occurrence data are unavailable (e.g., Berland et al. 2008, Mather et al. 2010, Waterhouse et al. 2010). As with all large area models, we recommend using our results for strategic planning, and suggest using finer-scaled data products, such as aerial photo interpretation habitat inventories (e.g., Waterhouse et al. 2008, Burger et al. 2009) for tactical planning (e.g., placement of protections or management guidelines, Waterhouse et al. 2010). For future work on coast-wide assessments of potential marbled murrelet habitat changes, we suggest that a closer examination of the spatial patterns of change and loss in nesting habitat (e.g., edges, patch size, and connectivity) may be valuable, as harvesting may actually impact the suitability of nesting habitat in the surrounding intact forest (e.g., Burger 2002, Piatt et al. 2007, Malt & Lank 2007, 2009).

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Table 1. Marbled murrelet nesting habitat attributes for each of three habitat suitability models. Model 1 is the most exclusive, model 2 is intermediate, and model 3 is the most inclusive, in terms of definition of potential marbled murrelet nesting habitat.

Attributes	**Model 1**	**Model 2**	**Model 3**
Forest stand age	≥ 250 years	≥ 140 years	≥ 140 years
Forest stand height	≥ 28.5 m	≥ 28.5 m	≥ 19.5 m
Distance to ocean shoreline	500 m–30 km	0–50 km	0–50 km
Elevation			
Central & Northern Mainland Coast	≤ 600 m	≤ 600 m	≤ 900 m
Haida Gwaii	≤ 500 m	≤ 500 m	≤ 800 m
All other regions	≤ 900 m	≤ 900 m	≤ 1500 m

Table 2. Data sources used in derivation of 1978 and 2008 potential marbled murrelet nesting habitat. See Figure 2 for a flow diagram demonstrating how all datasets are integrated into the analysis.

Dataset	**Notes**	**Compiler**
Forest Inventory	Primary source of forest attribute information.	British Columbia Ministry of Forests and Range, Forest Analysis and Inventory Branch
Baseline Thematic Mapping (BTM)	Used in distance to ocean shoreline calculation and to supplement forest inventory.	British Columbia Ministry of Environment, Lands and Parks, currently housed with GeoBC, Integrated Land Management Bureau
British Columbia digital elevation model (DEM)	Elevation data (25 m resolution).	British Columbia Ministry of Sustainable Resource Management, Base Mapping and Geomatics Services Branch
Forest Disturbance Data		
Vegetation Resources Inventory (VRI)	Available for 1978-2008, primary harvest data.	see Sandvoss *et al.* 2005
RESULTS	Available for 1980-2008, harvest data for TFLs[†].	British Columbia Ministry of Forests and Range, Forest Analysis and Inventory Branch
Change detection layer (CDL)	Available for 2000-2008, harvest data for private lands (> 1 ha).	British Columbia Ministry of Forests and Range, Forest Analysis and Inventory Branch
National Fire Database (NFD)	Available for 1978-2005, source of forest fire disturbances.	British Columbia Forest Service, Protection Branch, but also see Parisien *et al.* 2006
Landsat change	Available for 1985-2008, used to fill known spatial/temporal gaps in other data sources.	By the authors, specifically for the purpose of this study

[†] TFLs – Tree Farm Licences

Table 3. Estimates of availability and changes to potential marbled murrelet nesting habitat in 1978 and 2008, using three habitat suitability models. Loss and recruitment represent negative and positive respectively, sources of change to available habitat.

	Available Habitat (ha)		**Loss***		**Recruitment† (ha)**	**Net Change (ha)**	**% Change**
	1978	**2008**	**ha**	**(%)**			
Model 1							
West & North Vancouver Island	442613	384579	113316	(25.6)	55282	-58034	-13.1%
East Vancouver Island	32145	27005	5416	(16.8)	276	-5140	-16.0%
South Coast	139346	114329	38422	(27.6)	13405	-25017	-18.0%
Central Coast	298887	330384	64212	(21.5)	95711	+31497	+10.5%
North Coast	228680	243404	18512	(8.1)	33236	+14724	+6.4%
Haida Gwaii	221183	188933	35407	(16.0)	3157	-32250	-14.6%
Total	***1362854***	***1288634***	***275287***	***(20.2)***	***201067***	***-74220***	***-5.4%***
Model 2							
West & North Vancouver Island	808345	591019	225685	(27.9)	8359	-217326	-26.9%
East Vancouver Island	125054	91882	33918	(27.1)	746	-33172	-26.5%
South Coast	240394	200990	62438	(26.0)	23034	-39404	-16.4%
Central Coast	630197	526622	112365	(17.8)	8790	-103575	-16.4%
North Coast	475090	431566	52858	(11.1)	9334	-43524	-9.2%
Haida Gwaii	310635	267859	45095	(14.5)	2319	-42776	-13.8%
Total	***2589715***	***2109938***	***532359***	***(20.6)***	***52582***	***-479777***	***-18.5%***
Model 3							
West & North Vancouver Island	1139886	846355	304271	(26.7)	10740	-293531	-25.8%
East Vancouver Island	198840	151043	48657	(24.5)	860	-47797	-24.0%
South Coast	566278	502973	98485	(17.4)	35180	-63305	-11.2%
Central Coast	1253628	1105271	164345	(13.1)	15988	-148357	-11.8%
North Coast	1033029	968185	85998	(8.3)	21154	-64844	-6.3%
Haida Gwaii	512357	452934	66763	(13.0)	7340	-59423	-11.6%
Total	***4704018***	***4026761***	***7568519***	***(16.3)***	***91262***	***-677257***	***-14.4%***

* Habitat loss is area of 1978 habitat that is lost, by 2008, through forest disturbance.

† Habitat recruits from non-habitat in 1978 to Model 1 habitat in 2008 if, by aging for 30 years, stand age crosses from < 250 to ≥ 250 and satisfies the other requirements of the model. Habitat recruits from non-habitat in 1978 to Model 2 (or Model 3) habitat in 2008 if, by aging for 30 years, stand age crosses from < 140 to ≥ 140 and satisfies the other requirements of the model.

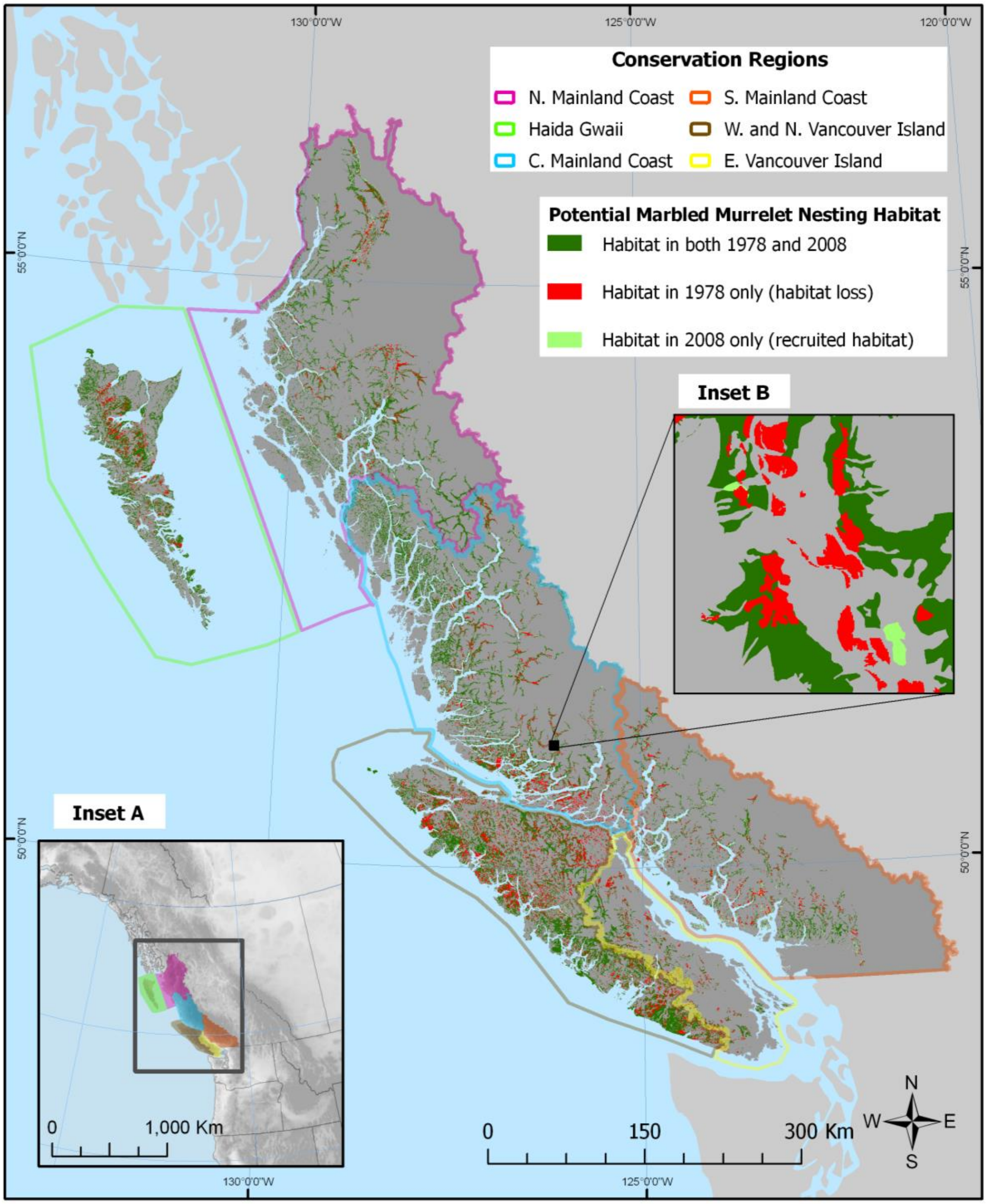

Figure 1. Six conservations regions for management of old-growth marbled murrelet nesting habitat in British Columbia (Inset A), with results from analysis of change to potential nesting habitat using the intermediate (Model 2) definition of habitat. Example of detailed view of habitat results provided in Inset B.

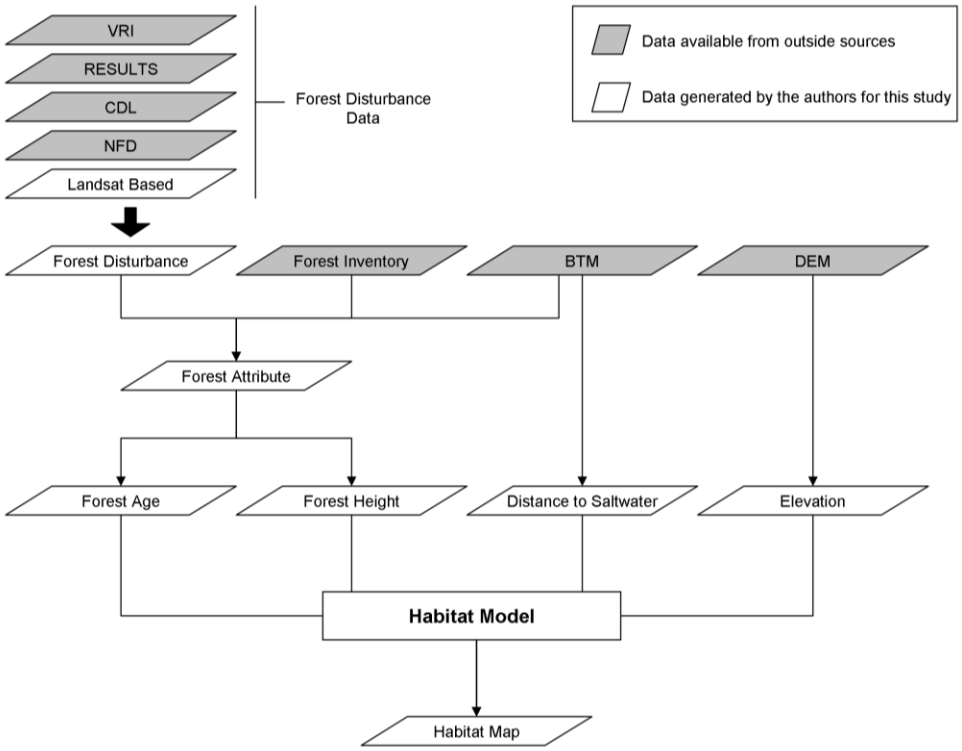

Figure 2. Flowchart, diagramming how input data sources (see Table 2) are combined to generate datasets on environmental variables used in three marbled murrelet nesting habitat models.