Change in Available Marbled Murrelet Nesting Habitat from 1978 to 2008 in British Columbia, Canada

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Abstract

The Marbled Murrelet, *Brachyramphus marmoratus,* is considered an old-growth dependent species, nesting in old growth trees in the coastal forests of North America. Concern over the loss of nesting habitat in British Columbia, due mainly to forest harvest, led to a conservation assessment of Threatened by the Committee on the Status of Endangered Wildlife in Canada, and subsequent listing of the species under the Canadian *Species at Risk Act*. Information on the availability and patterns of change in murrelet nesting habitat is essential for making land use decisions and determining and implementing conservation actions for this high-profile, wide-ranging species at risk. We modelled suitable Marbled Murrelet nesting habitat for the coast of British Columbia at two points in time, 1978 and 2008, and quantified the rate of habitat loss and net change in available habitat over this 30 year time period. We used the recommendations from the Canadian Marbled Murrelet Recovery Team and forest cover attributes to perform large scale mapping of available nesting habitat. We present habitat loss and change estimates as a range of values, reflecting both conservative and pre-cautionary scenarios. We estimated that 16.3 – 22.1% of nesting habitat was disturbed over the 30 year study period, with higher rates of disturbance in the most likely Marbled Murrelet breeding habitat class (20.2 – 24.5%). If recruitment of habitat over the 30 year period is considered, then the net change in available nesting habitat was estimated to be 14.4 – 18.4%. Our estimates are consistent with previous analyses of rates of Marbled Murrelet habitat change in British Columbia. This work did not examine the spatial configuration of habitat disturbances, and we suggest that future work should aim to quantify these properties as they are known to impact the suitability of remaining Marbled Murrelet nesting habitat.

Key Words: Marbled Murrelet, British Columbia, nesting habitat, model, mapping change

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 (CMMRT 2003). The population of Marbled Murrelets increases with latitude from Northern California to Alaska, with the majority of the global population found in Alaska (Stauffer et al. 2004; Nelson et al. 2006). It is estimated that British Columbia is home to approximately 99,600 murrelets (72,600 - 125,600; Bertram 2007), but details of the spatial distribution of the population within British Columbia are limited, especially in remote locations. While marine surveys, along with historical anecdotes of abundance, have suggested a sharp decline in murrelet populations in some areas, other quantitative data suggest some stable populations in British Columbia (Kelson et al. 1995; Burger 2002; Lank et al. 2003). However, historical information on the number of Marbled Murrelets in British Columbia and population or demographic data is especially limited for this elusive species (CMMRT 2003).

The Canadian population of marbled murrelets was assessed as Threatened in 1990, and again in 2000, by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), resulting in the legal listing of the Marbled Murrelet under the Canadian *Species at Risk Act* (*SARA)* in 2003. With limited information on population status (e.g., decline of mature individuals), the Marbled Murrelet COSEWIC assessment was based on an observed, estimated, inferred or suspected reduction in the extent of old-growth forest nesting habitat over three Marbled Murrelet generations (COSEWIC 2000). The Marbled Murrelet conservation assessment triggered a Threatened status based on an estimate of 24% decline in nesting coastal old growth forest habitat in British Columbia over a 27 year period (M. Eng, *pers. comm.*). The COSEWIC conservation assessment also discussed threats in the marine environment, including fisheries by-catch and oil spills (COSEWIC 2000). 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 (Norris et al. 2007). Provincially, Marbled Murrelet is assessed as a 'red-list' species, a species considered to be a candidate for provincial endangered or threatened listing. The Marbled Murrelet is also an Identified Wildlife Species and hence managed under British Columbia's *Forest and Range Practices Act* (Burger 2002; CMMRT 2003; Lank et al. 2003).

Loss of terrestrial nesting habitat is considered the primary threat to Marbled Murrelet populations range-wide (CMMRT 2003; Piatt 2007), which is well supported by the literature. For example, radar inventory techniques and offshore counts of individual Marbled Murrelets have been used to demonstrate a positive correlation between the amount of nearby nesting habitat and the number of murrelets nearby or entering large watersheds (e.g., Burger 2001; Miller et al. 2002; Raphael et al. 2002). Marbled Murrelet nesting habitat has been well characterized at landscape, stand and tree levels (e.g., Burger 2002; Zharikov et al. 2007; Zharikov et al. 2006). Marbled Murrelet nests are typically found in trees with large branches (>15 cm diameter) and sufficient epiphytic growth (Nelson 1997). Trees with these characteristics are almost always the oldest, at least 250 years of age, the tallest (> 28.5 m high; CMMRT 2003), and as such also have the greatest timber value. Marbled Murrelets do not appear to favour specific tree species; rather they locally select trees that provide a suitable platform for nest building (Burger 2002). Associations of nest sites with other macro-habitat features, such as elevation, distance-to-sea, and vertical canopy complexity, have also been investigated in order to characterize suitable habitat over increasing scales (Burger 2002). For example, canopy gaps at the stand level are considered to be important, likely to facilitate access to the tree by this awkward flyer (Burger 2002). Nest trees are generally found up to 50 km inland but mostly within 30 km from the shoreline, as birds are limited by the commuting distance from foraging areas (CMMRT 2003; Yen et al. 2004).

Quantifying the rate of change in available Marbled Murrelet old-growth nesting habitat 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 (Burger 2002). In addition, information on availability and patterns of change in habitat provide land managers with essential data for making land use decisions and determining and implementing conservation actions for species at risk. Finally, these data are necessary for COSEWIC's re-assessment of the conservation status of Marbled Murrelet in Canada, currently scheduled for 2010.

The goal of this research was to quantify the rate of change in available Marbled Murrelet nesting habitat over the past 30 years, equivalent to three Marbled Murrelet generations, for the coast of British Columbia. We map forest conditions in two time periods, 1978 and 2008; apply a Marbled Murrelet nesting habitat model and quantify nesting habitat for the years 1978 and 2008; and finally, we quantify the rate of change in nesting habitat between the two time periods. We discuss the usefulness and the limitations of this mapping approach for deriving estimates of species habitat change at a provincial scale, and suggest future work that would contribute to the assessment of Marbled Murrelet nesting habitat change in British Columbia.

Methods

The study area included the entire coast of British Columbia, the current range of the breeding population of Marbled Murrelets in Canada (CMMRT 2003). The study area was 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 are based on forest districts, land and wildlife management regions, and ecosection boundaries and each region differs in the current estimated abundance of Marbled Murrelets and in conservation priorities, as outlined by the Canadian Marbled Murrelet Recovery Team (CMMRT 2003).

Marbled Murrelet Nesting Habitat Model Selection

Several province-wide models of Marbled Murrelet nesting habitat have been developed. The Canadian Marbled Murrelet Recovery Team (hereafter CMMRT 2003) established guidelines for selecting suitable Marbled Murrelet nesting habitat in British Columbia (CMMRT 2003). The CMMRT characterized Marbled Murrelet nesting habitat as 'most likely', 'moderately likely', and 'least likely', providing parameter estimates for each habitat class (CMMRT 2003). Burger et al. (2005) evaluated these suggested parameters in the north coast of British Columbia*,* whereby the most and moderately likely habitat criteria were combined into a single habitat class, and least likely habitat considered non-habitat. This binary model used tree age, tree height, canopy closure, elevation, and distance-to- sea to define Marbled Murrelet nesting habitat (Burger 2005). When tested against aerial habitat surveys, 99% of sites (84/85) modeled as habitat contained some Marbled Murrelet habitat attributes (Burger et al. 2005). Chatwin and Mather (2007) also mapped murrelet habitat in British Columbia using a binary model with most and moderately attributes combined; however, in this case breeding habitat was modeled as >140 years (equivalent to the CMMRT 'most likely' and 'moderately likely' classes) and tree height >28.5m (equivalent to the CMMRT 'most likely' class). Elevation classes associated with habitat varied regionally (Table 1) with a distance-to-sea criteria of 50 km (Chatwin and Mather 2007). Tomlins and Gray (2007) used the same suite of parameters as Chatwin and Mather (2007) in an assessment of change to Marbled Murrelet habitat for the Sunshine Coast Forest District.

Other macrohabitat features, including site productivity index, slope, aspect, forest species, crown closure, and vertical canopy complexity, have been explored in some Marbled Murrelet breeding habitat models (e.g., North Coast Regional Model, Burger et al. 2005). Some of these criteria are correlated: for example; site index productivity is a function of forest stand height at 50 years, and was correlated with height class (Leckie & Gillis 1995). Results from Burger et al. (2005) suggested that slope was a neutral variable in habitat prediction, and although it has been suggested that aspect could play a role in determining suitable habitat (e.g., south facing slopes would likely be drier and have less epiphyte development; CMMRT 2003), there has been no evidence to support its use as a reliable predictor of Marbled Murrelet breeding habitat. Forest species composition varies regionally and also lacks reliability as a predictor of Marbled Murrelet breeding habitat (Burger et al. 2005). The CMMRT (2003) recognized that gaps in the canopy are important for Marbled Murrelet habitat and have included canopy closure and vertical complexity in their list of potential parameters for habitat modelling; however, both parameters are poorly captured in large area forestry datasets (CMMRT 2003). Some regional Marbled Murrelet breeding habitat models have used weighted attributes as inputs for habitat modelling (Holt 2004; Burger et al. 2005). Weighting input attributes resulted in several categories of Marbled Murrelet nesting habitat (e.g., superior, good, fair, nil; Holt 2004). While the weighted regional model of Burger et al. (2005) performed slightly better at identifying good or better habitat than a model based on the CMMRT attribute definitions; however a coast-wide model may be optimal, particularly when large area and coarse data sets are used as input. It should also be noted that the highest weighting went to tree height and tree age which are included in all models discussed above.

We implemented a three class model based on the habitat parameters outlined by the CMMRT (2003) (Table 1). Our classes included 'most likely' habitat, 'moderately likely' habitat, and 'non-habitat', and are equivalent to the CMMRT's most likely, moderately likely, and least likely habitat classes (CMMRT 2003). Forest attributes included stand age and height, and terrain attributes included distance-to-sea and elevation. Distance-to-sea was calculated as the Euclidean distance from salt water coastlines. The maximum elevation considered varied by conservation region, as recommended by the CMMRT (Table 1). Spatial data for forest age, forest height, elevation, and distance-to-sea were combined in GIS using a rule-based approach to create Marbled Murrelet nesting habitat in 1978 and 2008. Locations must have met all the criteria associated with 'most likely' (Table 1) to be classified as 'most likely' habitat. For a location to be classified as 'moderately likely' habitat, attribute variables could be a combination of 'most' and 'moderate' values, or all 'moderately likely' values (Table 1).

Data Sources

Several data sets were used to model Marbled Murrelet nesting habitat in 1978 and 2008. The primary data set was the continuous forest cover, projected to 2000 forest conditions. Polygons, the spatial unit for the forest inventory, representing forest stands, included age and height attributes. Stand age was the average age, in years, of the forest stand and was typically estimated indirectly from aerial photographs. Stand ages are represented in categories: one to 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 actual stand age becomes increasingly difficult as forests reach maturity. Stand height was also interpreted directly from aerial photography and reported in metres in the forest inventory data set. In areas where the seamless forest cover was absent (i.e., south-east Vancouver Island and private lands) Baseline Thematic Mapping (BTM) (British Columbia Ministry of Environment, Lands and Parks 1995, currently housed with GeoBC, Integrated Land Management Bureau) data were used. BTM is visually interpreted from Landsat imagery from the early and mid 1990s and provides information on stand age, which is reported as age categories: old forest (> 140 years), young forest (20 - 140 years), and recently logged (< 20 years). Height variables were unavailable within BTM. The BTM also provided data on sea locations for the distance-to-sea model parameter. Elevation was determined using the digital elevation model (DEM), which has a spatial resolution of 25m and was created from 1:20000 Terrain Research Information Management data (Province of British Columbia, 1996). These data were interpolated using a linear interpolation process and the DEM is reported to be accurate within 10m (BCMSRM 2002).

To back- and forecast forest conditions to 1978 and 2008, respectively, several additional data sets were required (Table 2). While the seamless forest cover provided data on base conditions in 2000, the vegetation resource inventory (VRI) supplied information on harvest date and was the primary source of data on 1978 and 2008 forest conditions, except within Tree Farm Licences (TFLs). Reporting Silviculture Updates and Land status Tracking System (RESULTS, see http://www.for.gov.bc.ca/his/results/index.htm) is a dataset generated from licensee self reporting of harvesting activities. RESULTS data are available from 2004, with some records dating back to 1980, although much of the data prior to 2004 were missing. Additional harvesting is captured in a Landsat-based change detection layer (CDL) from 2000 to 2008 (Morrison per com, 2009). CDL does not include change that occurs in TFLs and only reports harvests greater than 1 ha. To create a change layer similar to CDL for years prior to 2000, and to identify disturbances occurring in the TFLs, Landsat Thematic Mapper (TM) imagery was employed. Landsat TM was first available in 1985. Finally, forest fires were accounted for using the Canadian Forest Service National Fire Database (NFDB), which inventories forest fires up to 2005. Forest fire information since 2005 was not available (Parisien et al 2006).

Mapping forest condition and detecting change

Maps of 1978 and 2008 forest age and height were generated by integrating forest disturbance data with base seamless forest cover data representing circa 2000 forest age and height. Five datasets, organized as Geographic Information System (GIS) layers, were integrated to identify forest disturbances: 1) VRI harvest from 1978 to 2008; 2) RESULTS; 3) CDL; 4) NFDB; and 5) 1985 to 2008 Landsat-based change detection

(Table 2). Datasets one to four were obtained from various provincial and national government agencies (reviewed above); dataset five was generated using Landsat images. We captured disturbances that occurred prior to 2000 and also within TFLs post 2000. Care was taken to use best available imagery and to minimize the effect of cloud cover. The enhanced wetness difference index (EWDI) algorithm (Franklin et al. 2001, 2002), useful for detecting large forest clearings, was the basis for change detection and applied following the procedure outlined by Han et al. (2007). In summary, wetness indices are generated for two image dates and differenced to generate a EWDI layer. Locations with no change will have an EWDI value near zero and natural break in a frequency distribution of EWDI values is used as a change threshold. Elevations above murrelet nesting habitat model requirements were excluded from EWDI change detection (excluded elevations range from 800m to 1500m). As with the CDL data set, disturbances smaller than 1 ha were excluded. The initial date for which Landsat TM images are available is 1985 and, as such, our Landsat change layer does not include disturbances from 1978–1985.

We relied on harvest reporting records in the Ministry of Forests and Range's Annual Reports from 1978 to 1985 (BCMFR1978 - 1985) to supplement the limited data on harvest prior to 1985. 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 is generated by adding harvest records from the Vancouver Forest Region and the Prince Rupert Forest Region. Totals for the Prince Rupert Forest Region were scaled by 0.44 to reflect the proportion of our study area that fall within the area. Using the VRI and RESULTS data layers, 176,000 ha of harvest were spatially detected during this time period. Thus, 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. We include this additional loss estimate in our results, assuming all the harvest occurred within Marbled Murrelet nesting habitat. Implications of this assumption are discussed.

Disturbances occurring after 1978 were assigned height and age values in 1978. The total disturbance layer was intersected with the mature (> 140 years) forest. Where disturbance areas completely overlapped with mature forest, age and height values were retained from the base data. When the overlap was partial (i.e., the disturbance area intersected partial with one mature forest polygon or with several different mature forest polygons) age and height values were assigned from the mature forest polygon with the longest shared edge. Some disturbance areas did not intersect any mature forest polygons (i.e., isolated disturbances or polygons). We treated these isolated disturbances (area of isolated disturbances provided in brackets below) in two ways: in West and North Vancouver Island (23,514 ha), Central Mainland Coast (13,047 ha), Northern Mainland Coast (18,636 ha), and Haida Gwaii (2,918 ha), these isolated disturbances were all assigned age and height variables consistent with moderately likely habitat in 1978. Assigning moderately likely habitat to these disturbances assumes that harvesting was typically occurring in older stands, but could lead to an overestimate of this habitat class in 1978. In the Sunshine Coast, Tomlins and Gray (2007) reported that upwards of 50% of harvests were occurring in young (<140 years) forests from 1985 to 2005. Similar conditions are anticipated in East Vancouver Island (41,516 ha) and the Southern Mainland Coast (39,679 ha), so in these regions the island disturbance polygons were assigned to the non-habitat class. The sensitivity of the results to these assumptions were tested and results are reported for isolated disturbances assigned as above (Table 7) as well as with isolated polygons treated as most likely habitat and moderately likely respectively (pre-cautionary isolated polygon assumptions; Table 7).

The updated forest conditions provided forest attribution to the 1978 Marbled Murrelet nesting habitat model. For the 2008 model, forest age and height layers were created by removing all identified changes from suitable Marbled Murrelet nesting habitat classes. The stand ages reported in the 2000 base data were updated to represent 2008 conditions. As trees age, stand height growth slows, reaching a constant once a stand is mature (Ryan & Yoder 1997). For both 1978 and 2008, we modelled stand height as a constant, with the assumption being that those forest stands approaching and within the suitable height range for Marbled Murrelet habitat should have relatively small changes in height.

Change and loss of Marbled Murrelet breeding habitat

We quantify the amount of Marbled Murrelet habitat loss and an estimate of net habitat change, by habitat class, from 1978 to 2008. Marbled Murrelet habitat loss was calculated as the amount of disturbance within Marbled Murrelet modelled habitat subtracted from our 1978 habitat model. We also present an estimate of net Marbled Murrelet change, calculated by subtracting the 1978 and 2008 nesting habitat model outputs. Marbled Murrelet habitat change included habitat loss due to disturbance, but also habitat recruitment, as some forest stands moved into different attribute categories over the 30 year time period. We include a sensitivity analysis for the key assumptions (e.g., isolated polygons, missing data from 1978 to 1986; Table 7) and discuss the controversy of considering recruitment of old-growth forest within short time frames (e.g., 30 years) with respect to old-growth dependent species at risk.

Results

1978 Marbled Murrelet nesting habitat model

Our 1978 habitat model detected a total of 4.70 million ha of Marbled Murrelet nesting habitat; 1.36 million ha of most likely and 3.34 million ha of moderately likely habitat (Table 3). The Haida Gwaii and North and West Vancouver Island conservation regions had the greatest amount of Marbled Murrelet nesting habitat (Haida Gwaii: 512,357 ha overall, 1 million ha region; North and West Vancouver Island: 1,139,886 ha overall habitat, 2.15 million ha region), including the most likely habitat class (Haida Gwaii: 221,183 ha overall, 1 million ha region; North and West Vancouver Island: 205,867 ha overall habitat, 2.15 million ha region), after controlling for region size (Table 3). The Central Mainland Coast also held significant amounts of habitat (1,253,628 ha overall; 298,997 ha most likely habitat; 4.21 million ha region), with the other three regions having less and similar amounts of most and overall nesting habitat (after controlling for region area; Table 3).

Disturbance of 1973 Marbled Murrelet habitat

We detected a total of 1.06 million ha of disturbance within the study area from 1978 to 2008. Of this, 888,034 ha of disturbance were detected from 1986 to 2008, approximately 40,365 ha per year. Due to limited data prior to 1986, only 175,589 ha of disturbance were detected from 1978 to 1985. However, we estimated an additional 190,000 ha disturbance prior to 1986 using aspatial forest harvest records (see methods). When this aspatial estimate was added to our GIS disturbance estimate for the 1978 to 1985 period (365,589 ha total), it equates to approximately 45,698 ha disturbed per year, a more similar annual disturbance rate to the 1986 to 2008 estimate.

Based on our spatial disturbance data over the 30 year time period and the 1978 habitat model, 768,519 ha (16.3%) of Marbled Murrelet nesting habitat was lost due to disturbances (e.g., harvesting and fire), with a total of 275,278 ha (20.2%) of most likely habitat disturbed and 493,232 ha (14.8%) of moderately likely habitat disturbed coast-wide (Tables 4 and 7). Assuming the estimated 190,000 additional hectares of harvest from 1978 to 1985 was Marbled Murrelet habitat, the total estimate of potentially disturbed Marbled Murrelet overall nesting habitat (most likely plus moderately likely) was 958,519 ha (768,519 plus 190,000 ha), or 20.4% coast-wide (Tables 4 and 7). Disturbances to Marbled Murrelet habitat classes were not evenly distributed among the six conservation regions, with the West and North Vancouver Island region having the highest amount of disturbance to all habitat classes and the Northern Mainland Coast the lowest amount (Table 4). Generally the amount of disturbance was higher or similar within the most likely habitat class when compared to moderate habitat (Tables 4 and 7), except in the East Vancouver Island region, where the total amount of most likely habitat in 1978 was an order of magnitude lower than the other conservation regions (32,145 ha; Table 3).

2008 Marbled Murrelet nesting habitat and net change in available habitat

The 2008 Marbled Murrelet habitat model detected 4.03 million ha of murrelet nesting habitat overall, with 1.29 million ha of most likely habitat and 2.74 million ha of moderately likely habitat present coast-wide (Table 6). Although amount of remaining nesting habitat was much reduced, there were similar relative distributions of remaining habitat among the conservation regions as in 1978 (Tables 3 and 6). The 2008 habitat model reflects the documented disturbances to the forest from 1978 to 2008 (Table 4) but also captures some undisturbed forest stands that did not meet the attribute requirements for Marbled Murrelet habitat in 1978 but did meet these criteria in 2008. Since coastal forest stands were 'aged' over the 30 year period, some habitat recruited into the Marbled Murrelet habitat classes from the 1978 to the 2008 habitat models (e.g., 130 year old stand would recruit from the non-habitat class to moderate habitat, assuming the other moderate habitat attributes were met). A total of 201,067 ha of forest habit recruited from moderately likely habitat to the most likely habitat class, and 91,262 ha recruited from the non-habitat class to moderately likely habitat class (Table 5).

Considering both loss of Marbled Murrelet habitat due to the spatially detected disturbances and the above estimates of modelled recruitment, this represented a net change in Marbled Murrelet habitat of 14.4% from 1978 to 2008 (Table 7). Again, assuming the estimated 190,000 additional hectares of harvest from 1978 to 1985, the change in overall modelled habitat would be 18.4% coast-wide (Table 7). In 2008, there were 1.29 million ha of most likely habitat (5.4% less than 1978) and 2.74 million ha of moderately likely habitat (18.1% less than 1978). The net change in Murrelet nesting habitat varied by conservation region, with the greatest amounts of loss in West and North Vancouver Island and East Vancouver Island (25.8% and 24.0% respectively; Table 7). The greatest amount of most likely habitat class change occurred in the South Mainland Coast region (18.0%), while the greatest amount of moderately likely habitat change occurred in the West and North Vancouver Island region (33.8%).

Discussion

Quantifying the rate of loss and changes in available Marbled Murrelet old-growth nesting habitat is essential for making strategic land use decisions and determining and implementing conservation actions for this high-profile, wide ranging species at risk. Additionally, these data are necessary for COSEWIC's re-assessment of the conservation status of Marbled Murrelet in Canada, currently scheduled for 2010. We derived estimates of Marbled Murrelet habitat loss, due to harvest and fire, and net change of Marbled Murrelet habitat, which included modelled estimates of habitat recruitment. We present and discuss our estimates as ranges, based on both conservative and pre-cautionary scenarios, which demonstrate the sensitivity of the estimate to some key assumptions, namely the treatment of isolated disturbance polygons and missing data from 1978 to 1985 (see methods) and the controversial role of habitat recruitment in estimates (discussed below).

Over the past three Marbled Murrelet generations or 30 years (three times 10 years/generation), we estimated that 16.3 - 22.1% of overall Marbled Murrelet nesting habitat had been removed coast-wide in British Columbia (Table 7). This estimate included the disturbance of 14.8 - 24.8% moderately likely habitat and 20.2 - 24.5% of most likely nesting habitat (Table 7), with the most likely habitat defined as the most likely stands containing the attributes necessary for nesting murrelets in British Columbia (CMMRT 2003). The North and West Vancouver Island conservation region had the greatest rate of habitat loss over the 30 year period (26.7%), and this was also the conservation region with the largest area of available overall and most likely nesting habitat (both 1978 and 2008, Tables 3 and 6). East Vancouver Island region also had high rates of habitat loss (24.5%), particularly the moderate habitat class (25.9%), although the amount of most likely habitat estimated in the region in 1978 was already relatively low compared to other conservation regions (Table 3).

Taking nesting habitat loss due to disturbance and habitat recruitment from 1978 to 2008 into consideration, our estimate of net change in available Marbled Murrelet nesting habitat was 14.4 -18.4% (Table 7). Harvesting and fire disturbances had the strongest impact on the most likely habitat class (20.2 – 24.5 % disturbance) compared to the moderately likely habitat class (14.8 – 15.5% disturbance). However, estimates of habitat recruitment generated 91,262 ha of habitat within the moderately likely class between 1978 and 2008, and 201,067 ha of moderate habitat recruited into the most likely habitat class based on a 30 year increase in tree age. The resulting estimate of net change in most likely murrelet habitat was 5.4%, and 18.0% for moderately likely habitat (Table 7). However, the recruitment or 'increase' in most likely habitat only indicates a potential increase in existing habitat quality, and interestingly, approximately one third of the modelled habitat recruited was within the Southern Mainland Coast conservation region, the region with the highest amount of urban development and highest human population density within British Columbia.

We used a pre-cautionary approach in our estimation of the amount of disturbance due to harvesting and fire between 1978 and 2008. First, we included an aspatial estimate of forest disturbance derived from annual harvest reports, in addition to our spatial estimates, acknowledging the limited availability of data on harvest prior to 1985. Another source of uncertainty was the treatment of disturbance areas that did not intersect mature forests, referred to as isolated disturbances, which were considered to be non-habitat in 1978 for East Vancouver Island and Southern Mainland Coast (based on Tomlins and Gray 2007) and moderate habitat in the remaining regions. This assumed that much of the forest harvest in East Vancouver Island and on the Southern Mainland Coast now occurs in second growth (Tomlins and Gray 2007). We explored the impact of this assumption by presenting an alternative pre-cautionary approach, where all isolated polygons were considered moderately likely habitat in East Vancouver Island and Southern Mainland Coast and most likely habitat elsewhere. These assumptions had a large impact on estimates of moderate and most likely habitat loss in East Vancouver Island and Southern Mainland Coast, where the isolated polygons were first considered non-habitat, but had only a small impact on the other regional and coast-wide estimates of habitat loss (Table 7). An additional source of underestimation in the harvest data layers was that harvests of less than 1 ha were not captured in both the CDL and the EWDI Landsat change detection algorithms.

Habitat models make use of environmental surrogates to indicate conditions suitable for wildlife. In models of Marbled Murrelet nesting habitat, forest stand age is used as a surrogate for higher quality microhabitat features, such as branch diameter and epiphyte cover (Waterhouse et al. 2002). Epiphytic bryophytes, which Marbled Murrelets use to make a nest cup (Burger 2002), may require anywhere from 100–400 years to develop (Waterhouse et al. 2002). Trees in which nests have been located in British Columbia have all been estimated to be older than 140 years, with most older than 200 years (Burger 2002). However, age thresholds are somewhat subjective, and the choice of 140 years as the lower limit is an artefact of forestry data age classes, rather than a clear threshold for murrelet habitat. Although tree age is a strong predictor of nest selection sites (Waterhouse et al. 2002), it is also a source of uncertainty in large area studies. Stand age is the average age, weighted by basal area of the dominant/codominant and high intermediate trees for the leading and second species in a polygon (Dorner et al. 2003). Visual interpretation of aerial photography is the primary source of the assignment of stand ages, and is less accurate than tree ring counts (Dorner et al. 2003). Stand age does not truly represent the time since the last disturbance as it may take many years for seedlings to establish, and the codominants are not always the oldest in the stand (Dorner et al. 2003). Thus, the possibility of overlooking suitable Marbled Murrelet nesting habitat exists if there are some patches of older trees within a predominantly younger stand. For example, Waterhouse and others (2002) found that two of their 45 polygons that contained nests were only classified as 80 years of age.

Given the uncertainty associated with forest age data, and the use of forest age as a surrogate for suitable murrelet breeding habitat, we suggest caution in interpreting our net change in available Marbled Murrelet habitat results, which include habitat recruitment. For example, the increases to the most likely habitat class from 1978 – 2008 for both the North Coast and Central Coast regions (Table 5) are, in part, a function of how stand ages have been calculated. As provincial datasets transitioned from age class to age-based recording, historical forest inventory class midpoints were commonly used as surrogate for actual stand age (Dorner et al. 2003). Using the midpoint of age classes to represent age, leads to overrepresentation of some forest ages (Dorner et al. 2003); on average stand age is overestimated (by 20.4 years) when stand are greater than 100 years (Dorner et al 2003). As such the large amount of habitat that has been recruited from moderately likely habitat to most likely habitat may not adequately reflect changes in habitat quality. Age classes are broad and, as with all large area ecological modelling, changes that make an area non-habitat become habitat or make moderate habitat become most likely habitat are estimated using simplified surrogate variables.

The issues associated with using tree or stand age to model Marbled Murrelet nesting habitat are indicative of the general strengths and challenges associated with large area habitat modelling (Nelson et al. 2006). Regional scale modelling of habitat is important for management and provides an approach for monitoring wildlife when population data are unavailable. The Marbled Murrelet nesting habitat model presented here is intended only to inform strategic planning and decision making. As with all large area modelling, we anticipate uncertainty at individual locations and suggest using broad scale mapping to identify areas where detailed data and study are required. At local scales, when detailed data are available or can be collected, additional variables such as vertical complexity provide model refinement.

The issues with available spatial data on forest disturbance, such as the missing 1 ha or less harvests and lack of complete data for the 1978 to 2005 period, suggests that our lower estimates of habitat loss and net change in Marbled Murrelet nesting habitat are an underestimate. However, our estimates of 16.3 – 22.1% habitat disturbance (20.2 – 24.5% disturbance to the most likely nesting habitat) and 14.4 – 18.4 % net change in available habitat are roughly similar to those reported in previous analyses of Marbled Murrelet nesting habitat change (18.3% disturbance and 12% net loss in the Sunshine Coast Forest District/1985 to 2005, Tomlin and Gray 2007; 24% habitat loss from harvest coast-wide/1973 to 2000, M.Eng, *pers. comm.*).

For future work, we suggest that a closer examination of the patterns of change in nesting habitat may be valuable. For instance, it is important to quantify the spatial pattern (e.g., edges, patch size, and connectivity) of nesting habitat change. The existence of large contiguous patches is considered a better conservation strategy for nesting Marbled Murrelet populations, largely due to potentially negative edge effects (e.g., microclimate, as well as increased predation; Burger 2002). Furthermore, the type of stand edge that occurs affects the level of impact on nesting sites. Marbled murrelet nesting habitat is impacted from fragmentation through the creation of hard forest edges (e.g., the edge of a clearcut), whereas natural edges (e.g., along a river) impact nesting habitat considerably less (CMMRT 2003). Along hard forest edges, nests become more susceptible to microclimate extremes and vulnerable to predation (CMMRT 2003). Thus, harvesting may actually impact the suitability of nesting habitat in the surrounding intact forest. This study did not account for edge effects, or fragmentation of forests, but future work should aim to quantify these properties as they are known to impact Marbled Murrelet nesting habitat (Meyer et al. 2002; Burger 2002).

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Table 1. Attributes and values used to model Marbled Murrelet nesting habitat in British Columbia.

Attributes	Most Likely Nesting Habitat	Moderately Likely Nesting Habitat*
Stand age class	≥ 250 years	140 – 249 years
Stand tree height	≥ 28.5 m	19.5 – 28.4 m
Distance from saltwater	500 m – 30 km	0-500 m & 30 – 50 km
Elevation		
Central & Northern Mainland Coast	≤ 600 m	600 – 900
Haida Gwaii	≤ 500 m	500 – 800
All other regions	≤ 900 m	900 – 1500

* Locations must have met all the criteria associated with most likely to be classified as such. For a location to be classified as moderately likely habitat, attribute variables could be a combination of most and moderate values or all moderately likely values.

Table 2. Data sources used for identifying forest loss (harvesting and fire) in coastal British Columbia between 1978 and 2008.

Data Source	**Time**	**Context**
Vegetation Resources Inventory (VRI) [1]	1978 – 2008	Primary harvest data set
RESULTS [2]	1980 – 2008	Supplementary harvest data
CDL [2]	2000 – 2008	Supplementary harvest data
National Fire Database [3]	1978 – 2005	Supplement disturbance data on forest fires
Landsat EWDI change [4]	1985 – 2008	Change from 1985 to 2000 and TFL change for 2000 to 2008

[1] Sandvoss et al. 2005
[2]Generated by the British Columbia Ministry of Forests and Range, Forest Analysis and Inventory Branch
[3]Compiled by the British Columbia Forest Service, Protection Branch, but also see Parisien et al. 2006
[4]Generated by the authors for use in this analysis

Table 3. Available Marbled Murrelet nesting habitat area in British Columbia in 1978.

	Available Habitat 1978 (ha)		
	Most Likely	**Moderately Likely**	**Overall**
West & North Vancouver Island	442613	697273	1139886
East Vancouver Island	32145	166695	198840
South Coast	139346	426932	566278
Central Coast	298887	954741	1253628
North Coast	228680	804349	1033029
Haida Gwaii	221183	291174	512357
Total	1362854	3341164	4704018

Table 4. Loss of 1978 Marbled Murrelet nesting habitat (ha) in British Columbia from 1978 to 2008.

	Most Likely	Moderately Likely	Overall
West & North Vancouver Island	113316	190955	304271
East Vancouver Island	5416	43241	48657
South Coast	38422	60063	98485
Central Coast	64214	100131	164345
North Coast	18512	67486	85998
Haida Gwaii	35407	31356	66763
Total	275287	493232	768519 958519*

*Includes the estimated 190,000 ha of harvest from Ministry of Forests and Range's Annual Reports from 1978 to 1985 (BCMFR1978 - 1985).

Table 5. Recruitment of modelled Marbled Murrelet nesting habitat in British Columbia from 1978 to 2008.

	Habitat Recruitment (ha)	
	Moderate to Most Likely [1]	**Non-Habitat to Moderate** [2]
West & North Vancouver Island	55282	10740
East Vancouver Island	276	860
South Coast	13405	35180
Central Coast	95711	15988
North Coast	33236	21154
Haida Gwaii	3157	7340
Total	201067	91262

[1] Habitat recruits from moderately likely habitat in 1978 to most likely habitat in 2008 if, by aging for 30 years the stand age crosses from < 250 to ≥ 250 and satisfies the other requirements of most likely habitat.
[2] Habitat recruits from non-habitat in 1978 to moderately likely habitat in 2008 if, by aging for 30 years the stand age crosses from < 140 to ≥ 140 and satisfies the other requirements of moderately likely habitat.

Table 6. Available Marbled Murrelet nesting habitat area in British Columbia in 2008.

	Available Habitat 2008 (ha)		
	Most Likely	Moderately Likely	Overall
West & North Vancouver Island	384579	461776	846355
East Vancouver Island	27005	124038	151043
South Coast	114329	388644	502973
Central Coast	330384	774887	1105271
North Coast	243404	724781	968185
Haida Gwaii	188933	264001	452934
Total	1288634	2738127	4026761

Table 7. Estimates of loss and change in available Marbled Murrelet nesting habitat in British Columbia from 1978 to 2008.

	1978 model minus disturbance			1978 model minus disturbance w/ pre-cautionary 'isolated polygon' assumptions			1978 model minus 2008 model (includes habitat recruitment)		
Conservation Region	**Most Likely**	**Moderately Likely**	**Overall**	**Most Likely**	**Moderately Likely**	**Overall**	**Most Likely**	**Moderately Likely**	**Overall**
West & North Vancouver Island	25.6	27.4	26.7	30.9	24.0	26.7	13.1	33.8	25.8
East Vancouver Island	16.8	25.9	24.5	16.8	50.8	45.3	16.0	25.6	24.0
South Coast	27.6	14.1	17.4	27.6	23.4	24.4	18.0	9.0	11.2
Central Coast	21.5	10.5	13.1	25.8	9.1	13.1	-10.5	18.8	11.8
North Coast	8.1	8.4	8.3	16.2	6.1	8.3	-6.4	9.9	6.3
Haida Gwaii	16.0	10.8	13.0	17.3	9.8	13.0	14.6	9.3	11.6
Total	20.2	14.8	16.3	24.5	15.5	18.1	5.4	18.0	14.4
			*20.4			*22.1			*18.4

*Includes the estimated 190,000 ha of harvest from Ministry of Forests and Range's Annual Reports from 1978 to 1985 (BCMFR1978 - 1985).

Figure 1. Study area, showing six conservation regions for Marbled Murrelet management as outlined by the Canadian Marbled Murrelet Recovery Team (CMMRT 2003).