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Assessing Habitat Quality of Marbled Murrelet Nest Sites on the Queen Charlotte Islands/Haida Gwaii, by Algorithm, Airphoto Interpretation, and Aerial Survey Methods

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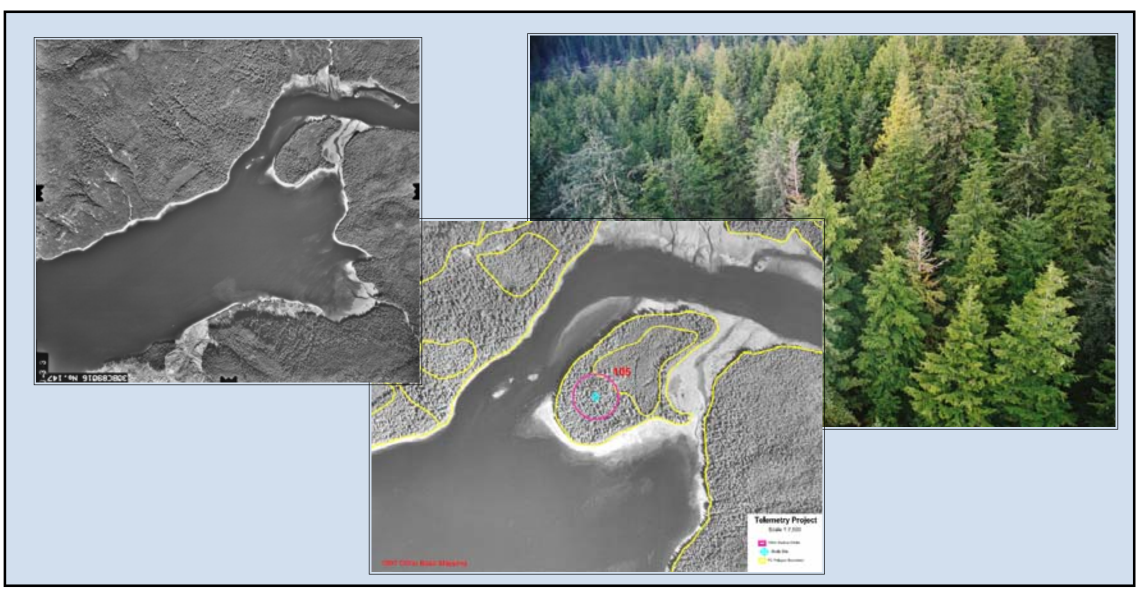

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EXECUTIVE SUMMARY

On the Queen Charlotte Islands/Haida Gwaii, we evaluated the quality and characteristics of Marbled Murrelet (*Brachyramphus marmoratus*) nesting habitat in forests >140 years old. Using seven nest sites and 30 randomly selected sites, we applied two standardized methods—airphoto interpretation and low-level aerial surveys from a helicopter—to describe topography, stand structure, and habitat quality class of patches centered on the sites. We also calculated the Habitat Suitability Index of sites using an existing GIS map-based habitat suitability algorithm.

Airphoto interpretation indicated that nesting habitat used by murrelets had more complex forest canopies, with greater occurrences of small gaps and taller canopy trees, including greater occurrences of large trees dominating at least 5 m above the main canopy.

Nesting habitat described by the aerial survey method indicated murrelets used patches with greater amounts of large trees >28 m tall, trees with potential platforms, and trees with moss pads. Topography as described by aerial surveys and elevation was not a strong indicator of nesting habitat. Nor were nest sites effectively differentiated from random sites by using the Habitat Suitability Index produced from the GIS map-based habitat suitability algorithm.

Both the airphoto interpretation and aerial survey methods revealed that the nest sites occurred across a range of habitat quality classes, but the patches in which they occurred were more often classified as higher in habitat quality than were the random patches. The airphoto interpretation and aerial survey classifications corresponded significantly. Differences were mostly attributable to differences in rankings of patches assigned to the lower habitat quality classes.

Scale of implementation of the aerial survey method—i.e., a comparison of patch-level versus polygon-level (forest stand) evaluations—also suggested that habitat quality of the site was influenced by the spatial scale at which it was assessed. Larger polygons in which patches occurred were more often classified lower in quality than the patches themselves. Overall, our findings support the notion that habitat patches with features important to nesting murrelets are best identified by integrating the airphoto interpretation and aerial survey methods.

KEYWORDS

Marbled Murrelet, *Brachyramphus marmoratus*, habitat quality, nesting habitat, assessment, classification, survey methods, airphoto interpretation, aerial survey, Queen Charlotte Islands, Haida Gwaii, coastal British Columbia.

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INTRODUCTION

The Marbled Murrelet (*Brachyramphus marmoratus*), an Alcid seabird, nests in older coastal forests ranging from northern California to Alaska (Burger 2002). Its management is a high priority in British Columbia (B.C. Ministry of Environment 2004) where its population—estimated to be 60 000 to 80 000 individuals (Burger 2002)—is considered threatened based on a perceived decline owing to the harvesting of old forest (Committee on the Status of Endangered Wildlife in Canada 2000).

Some of the methods currently used to classify habitat quality and suitability for nesting Marbled Murrelets include GIS habitat algorithms (Tripp 2001), airphoto interpretation (Donaldson 2004), and low-level aerial surveys conducted by helicopter (Burger et al. 2004). The Canadian Marbled Murrelet Recovery Team (CMMRT) recommended an approach for identifying and mapping the Wildlife Habitat Areas of Marbled Murrelets by applying three assessment methods—algorithm, airphoto interpretation, and aerial survey—in sequence (CMMRT 2003). This approach is outlined in the species account of the *Identified Wildlife Management Strategy* for management of Wildlife Habitat Areas for Marbled Murrelets (B.C. Ministry of Environment 2004). Initially, the usual method of assessing habitat potential at the landscape level is to apply a GIS map-based habitat suitability algorithm and identify forest cover polygons in terms of habitat quality. Then the habitat quality of each polygon is verified by means of aerial surveys or ground surveys. These surveys ensure that key nesting structures, especially potential nest platforms, are confirmed as present in the proposed management stands (B.C. Ministry of Environment 2004). Key nesting structures are defined as limbs or deformities >15 cm in diameter including any moss cover.

Intermediate between the convenient, lower cost map-based method and the costly field-based aerial survey or ground methods is the airphoto interpretation method; it may be used as an optional, intermediate step in assessing habitat quality (Donaldson 2004). Through the use of existing airphoto inventories, airphoto interpretation is a less costly method to apply over expansive areas than are aerial or ground surveys. Yet its effectiveness relies on whether it may narrow the selection of areas that need more intensive and costly assessment methods. Potential nest platforms cannot be identified on airphotos, but other stand characteristics that are indicative of murrelet habitat, such as large trees and stand structural complexity, can be described and ranked for habitat quality by the airphoto interpretation method (Donaldson 2004).

A GIS map-based habitat suitability algorithm for identifying murrelet habitat was originally developed by McLennan et al. (2000), and subsequently modified for the land-use planning process on Queen Charlotte Islands/Haida Gwaii (Holt 2004). More recently, a mapped layer based on the airphoto standards (Donaldson 2004) has been produced to assist land managers with planning. At a finer scale, aerial surveys have been used on the Queen Charlotte Islands/Haida Gwaii to help document the presence of key structures in stands of interest to forest operations, and to help verify the effectiveness of using airphoto interpretation for assessing and classifying Marbled Murrelet nest habitat.

On the Queen Charlotte Islands/Haida Gwaii, we applied two standardized methods—airphoto interpretation and low-level aerial surveys from a helicopter—at seven previously identified nest sites (Manley et al. 2001) and at 30 randomly selected sites in forests >140 years old. From existing databases, we also determined elevation and the Habitat Suitability Index (GIS map-based habitat suitability algorithm) of the sites. The goals of the study were to:

1. provide preliminary interpretations of murrelet nesting habitat on the Queen Charlotte Islands/Haida Gwaii; and

2. evaluate and compare effectiveness of the three classification methods, relative to their application for strategic and operational planning.

STUDY METHODS

Study Area

The study took place on the Queen Charlotte Islands/Haida Gwaii in north coastal British Columbia. The study area included portions of Graham Island and South Moresby Island, and it represented a number of biogeoclimatic ecosystem variants (Meidinger and Pojar 1991) including: the Coastal Western Hemlock submontane wet hypermaritime variant; the Coastal Western Hemlock montane wet hypermaritime variant; the Coastal Western Hemlock central very wet hypermaritime variant; and the Mountain Hemlock wet hypermaritime subzone. These variants are dominated by western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), western redcedar (*Thuja plicata*), and yellow-cedar (*Chamaecyparis nootkatensis*), with mountain hemlock (*Tsuga mertensiana*) occurring in the higher elevation subzone (Green and Klinka 1994).

Sampling Design

The seven nest sites used in this study were located in the year 2000 by radio telemetry methods (Manley et al. 2001). Murrelets were captured at night while they were feeding on the water off the southwest coast of Graham Island. A radio was attached to each captured bird by means of a subcutaneous anchor. Nest sites were located by tracking the radioed birds using helicopter surveys. Manley et al. did not confirm the actual nest trees by tree climbing. Rather, they confirmed the use of a site for nesting by noting repeated trips to the same general location by a radio tagged bird. Nest sites were located with GPS and marked on airphotos.

Given the small sample size, we defined the study area for sampling random locations as the perimeter of the cluster of actual nest sites (called the core area) plus a 5-km buffer, for a total area of 52 610 ha (Figure 1). The 5-km buffer is approximately twice the mean annual nest spacing distance reported for samples of nests in south coastal British Columbia

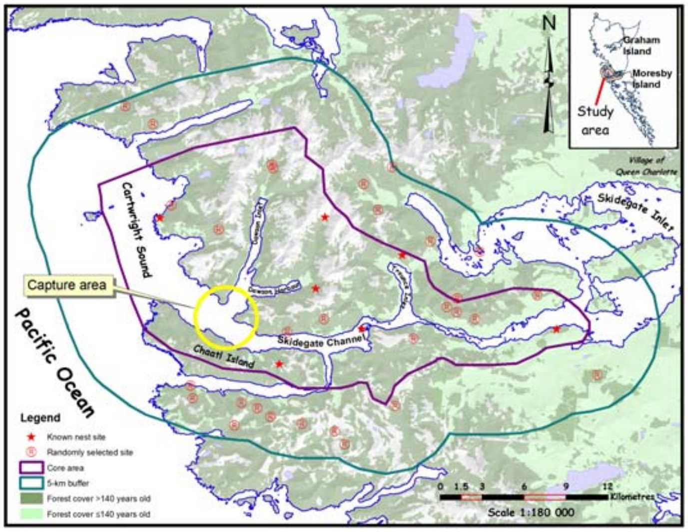

Figure 1. Map of study area. Study area = core area + 5-km buffer.

that had also been found through radio tracking (Zharikov et al. 2006). Within the study area we identified potential nest habitat according to the general age criteria (i.e., Most Likely and Moderately Likely) set out by the Canadian Marbled Murrelet Recovery Team (CMMRT 2003) and consistent with the ages of the nest sites (i.e., nest sites were trees >200 years old). In our study area, potential nest habitat consisted of 24 242 ha of forest aged >140 years old (11 237 ha in the core area, plus 13 105 ha in the buffer), all below 800 m elevation.

For comparison, we randomly selected 30 sites by using GIS to generate points for plot centers within the core area. Because elevation can influence stand structure, we then tested whether these 30 sites were representative of the available forest >140 years old by elevation. Using the Kolmogorov–Smirnov goodness-of-fit test (D'Agostino and Stephens 1986), we compared the distribution of the locations of randomly selected sites within each 100-m elevation contour with the distribution of the forest >140 years old within each contour. Elevation was calculated from a digital elevation model based on Terrain Resource Inventory Mapping (TRIM) data. The test showed no difference ($Z = 0.75$, $N = 8$ contours, $P = 0.62$) thus indicating that the random sites were representative of the elevational distribution of forested areas >140 years old.

Data Collection

To account for the uncertainty of the exact locations of murrelet nest sites, and to ensure that this study would be consistent with previous studies (Waterhouse et al. 2004), nest sites and random sites were assessed, according to both the airphoto interpretation and aerial survey methods (Burger 2004), using a plot with an estimated radius of 100-m centered on the GPS co-ordinate. The plots are hereafter called patches. When we applied the aerial survey method, we also made an overall assessment of the larger polygon (forest stand) containing the patch. The forest structure and topographic variables applicable to the airphoto interpretation method are listed in Appendix A, and the variables applicable to the aerial survey method are listed in Appendix B. To avoid potential bias, all sites were assessed blind, i.e., during the aerial surveys, the biologists were not aware of whether they were assessing a nest site or a random site nor was the airphoto interpreter aware of site classification.

In applying the aerial survey method, a field coordinator/navigator used a combination of 1:20 000 maps, airphotos, and GPS co-ordinates to locate all the sites. Habitat assessments were undertaken by two biologists using the standard protocol (Burger et al. 2004). The helicopter circled slowly around each site for 3 to 5 minutes. Still photos and video footage were collected at all sites.

In order to test the GIS map-based habitat suitability algorithm, a Habitat Suitability Index was generated for each site from an aggregated, weighted score (based on tree height, stand age, stand crown closure, and elevation) produced by the available algorithm for the study area (McLennan et al. 2000; Holt 2004). Following Holt (2004), aggregated scores were then assigned to one of four Habitat Suitability Index classes as follows: 54 to 60 = Very High, 51 to 53 = High, 46 to 50 = Moderate, <45 = Low. The higher the class the more likely the site will have greater densities of potential nesting platforms (McLennan et al. 2000; Holt 2004).

Analyses

Statistical analyses were limited by the small number of nest sites in our sample. Random sites represent *available* habitat, not necessarily *unused* habitat (Manly et al. 2002); therefore *use* versus *availability* comparisons indicate only if the habitat assessed at nest sites potentially differs from the habitat assessed at random sites. We used alpha = 0.05 as our level of significance, and considered alpha = 0.05 to 0.1 as having marginal significance.

We used non-parametric Wilcoxon tests in JMP 3.2.2. (SAS Institute Inc. 1997) and determined if significant differences occurred between nest patches and random patches for continuous and ordinal variables, although the latter tests are only approximate and have low statistical power. For nominal variables we relied on qualitative comparisons of trends between proportions of nest patches and random patches by variable classes, because samples were too small for Chi-square type tests. Potential associations among different variables were tested using:

• Spearman rank correlations (r_s) between continuous and ordinal variables,

• the Mantel–Haenszel statistic (Mantel and Haenszel 1959) between ordinal and nominal variables, and

• the Cochran–Mantel–Haenszel statistic (Mantel and Haenszel 1959) between nominal and nominal variables.

We used proportional odds logistic regression (SAS Institute Inc. 2003) to test, for the same site, how well a class determined by applying the airphoto interpretation method predicts what class would be assigned by applying the aerial survey method (see Appendix C). The resulting predicted probabilities represented the chance that an observation from a particular habitat quality class determined by the airphoto interpretation method fell into a particular class determined by the aerial survey method. Predicted probabilities for all the classes of the variable will sum to a score of 1.0. Predicted probabilities provide information similar to that of the sampling proportions, but slight differences may occur because of the ordinal model structure.

RESULTS

Describing Nesting Habitat

Elevation and Topography

The variables that describe site location and topography were not strong indicators of nest sites. Elevations of nest sites did not differ significantly from those of randomly selected sites (Table 1). For meso slope position interpreted from airphotos, nest patches (71%) occurred more often in the Mid slope position than did random patches (35%), but significant overall differences were not detected (Figure 2; Z = 0.82, P = 0.41). The results of the aerial survey method for slope position were also non-significant (Figure 2, Z = –0.21, P = 0.83). Although meso slope position determined by the airphoto interpretation method and slope position determined by the aerial survey method correlated significantly ($r_s = 0.47$; $P < 0.05$), we observed differences in the proportions of each by class (Figure 2).

The results of the aerial survey method showed that most nest patches were on steep grades—which reflected the general nature of the topography of the study area—and that grade differed little between nest patches and random patches (Figure 2; Z = 0.76, P = 0.43). Slope grade correlated with both meso slope ($r_s = 0.54$; $P < 0.05$) and slope position ($r_s = 0.56$; $P < 0.05$). Steeper slope grades were associated with both mid and upper positions of both.

Nest patches did not differ significantly from random patches in topographic complexity (Figure 2; Z = –1.4, P = 0.14). Topographic complexity was associated with slope position ($r_s = 0.43$; $P < 0.05$) and with slope grade ($r_s = 0.65$; $P < 0.05$), suggesting that complexity increases as slope position goes from Low to Upper and as slope grade increases.

Forest Cover, Canopy Gaps, and Canopy Closure

The proportions of the dominant types of cover (i.e., forest >140 years old, forest ≤140 years old, vegetated areas, and non-vegetated areas) estimated by the airphoto interpretation method did not differ significantly between nest patches and random patches (Table 1). Patches were mostly covered by forest >140 years old. Large gaps were not interpreted for any site in this study (Appendix A). Small gaps interpreted on airphotos were classified as Prevalent at all nest patches, but their occurrence varied at random patches, with some random patches being classified as Sporadic or None (Figure 3; no statistical test possible).

Estimates of crown closure that emerged from the airphoto interpretation method did not differ between nest patches and random patches. For both types of patches, 86% were classified Most Likely and 14% were classified Moderately Likely (Fisher Exact test P = 1.0). In contrast, at nest patches the estimates of canopy cover by the aerial survey method were more often classified as Most Likely than were random patches. I.e., of the nest patches 100% were classified Most Likely; and, of the random patches, 57% were classified Most Likely and 43% were classified Moderately Likely (Fisher's Exact Test, P = 0.03). Although the amounts estimated by the two methods for the same patch often differed by only 10%, this amount was enough to put the samples into different habitat classes (CMMRT 2003).

Overstorey Canopy and Structural Complexity

According to the airphoto interpretation method, nest patches tended to have more complex canopy structure than random patches (Figure 3; Z = –2.4, P = 0.02). Canopy complexity at most nest patches was Moderate to Very High, whereas random

Table 1. Mean values (± standard error) and non-parametric Wilcoxon tests for continuous variables estimated by the airphoto interpretation method.

Variable	Nest Patches (n = 7)	Random Patches (n = 30)	Z (P)
Elevation (m)	228 ± 69	269 ± 29	0.46 (0.50)
Forest cover >140 years old (%)	92.9 ± 5.7	84.8 ± 5.1	0.68 (0.50)
Forest cover ≤140 years old (%)	5.7 ± 5.7	11.8 ± 5.0	-0.51 (0.60)
Vegetated cover (%)	1.4 ± 1.4	2.3 ± 1.3	0.0 (1.0)
Non-vegetated cover (%)	0	1.0 ± 0.6	-0.82 (0.41)
Tree height (m)	31.7 ± 1.4	27.3 ± 1.2	1.83 (0.07)

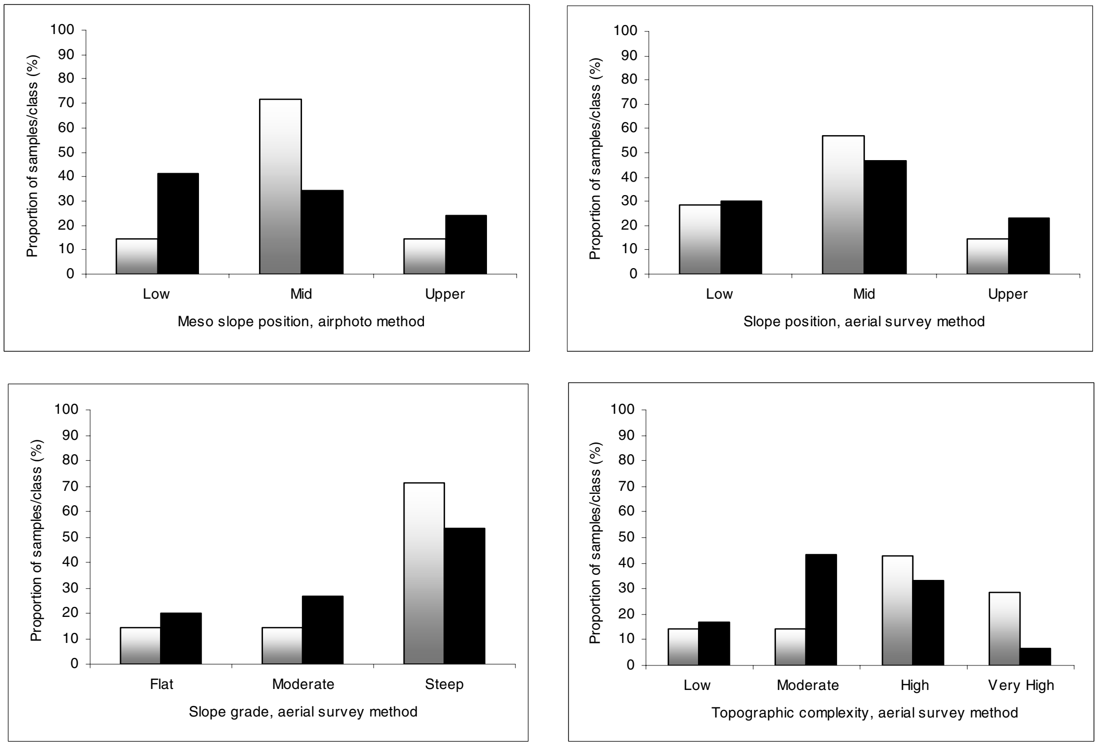

Figure 2. Comparison of nest patches (open histogram) and random patches (black), by class, using airphoto interpretation for meso slope position, and using aerial surveys for slope position, slope gradient, and topographic complexity.

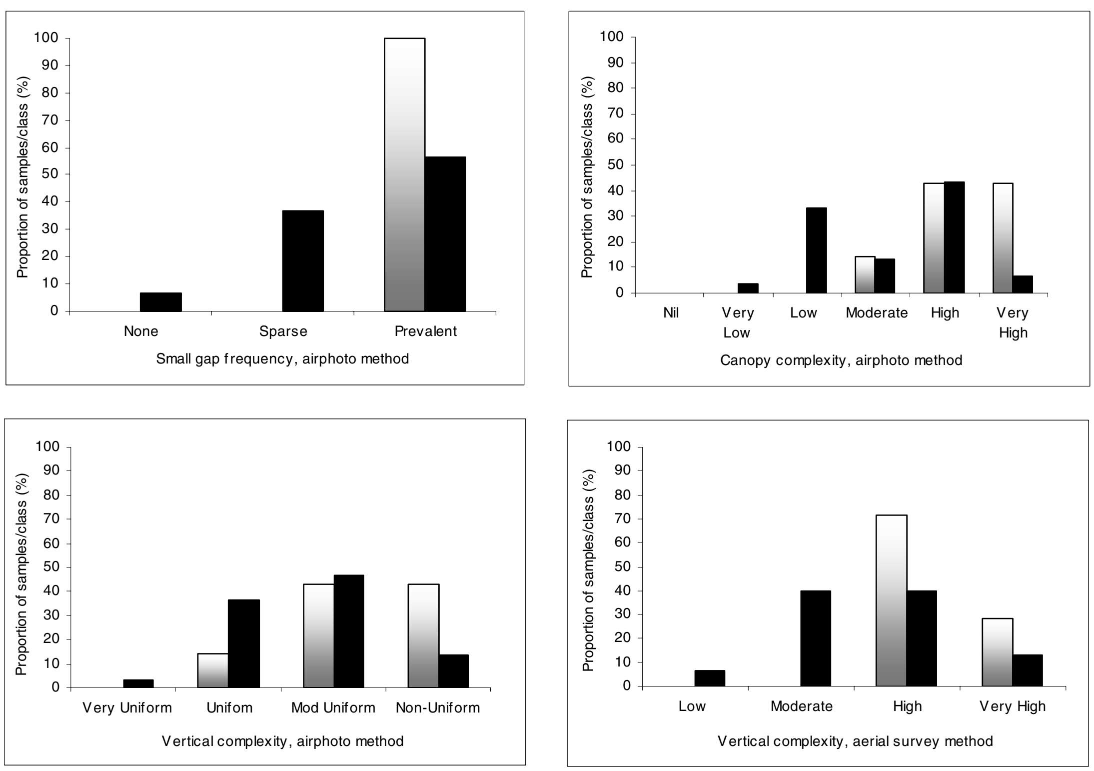

Figure 3. Comparison of nest patches (open histogram) and random patches (black), by class, using airphoto interpretation for occurrence of small forest gaps, and for canopy complexity and vertical complexity; and using aerial surveys for vertical complexity.

patches fell into the full range of classes (Figure 3). Also, airphoto interpretation revealed that nest patches and random patches differed significantly in terms of vertical complexity (Figure 3; Z = –2.1, P = 0.04). Nest patches were more often classified as Moderately Uniform and Non-Uniform, whereas random patches were more often classified as Uniform or Moderately Uniform. However, according to the results of the aerial survey method, nest patches and random patches differed marginally in terms of vertical complexity (Figure 3; Z = 1.76, P = 0.08). The vertical complexity of all nest patches was classified as either Very High or High, whereas 47% of random patches were classified as Moderate or Low. The airphoto interpretation variables describing forest structure—i.e., crown closure, canopy complexity, vertical complexity, and small gap occurrence—were significantly correlated ($P \leq 0.05$) with the aerial survey method's variable of vertical complexity (Tables 2 and 3). But, canopy closure classified by the aerial survey method, unlike crown closure classified by the airphoto interpretation method, correlated significantly with vertical complexity only (Tables 2 and 3).

Tree Height, Large Trees, Trees with Platforms, and Moss Development

Based on airphoto interpretation, trees were slightly taller in nest patches than in random patches, although this difference was of marginal statistical significance (Table 1; P = 0.07). Large trees—interpreted on airphotos as those dominant trees with large crowns at least 5 m above the main canopy—occurred at all nest patches but they were absent from 40% of random patches (Figure 4; no statistical test possible). As estimated by the aerial survey method, occurrences of large trees, i.e., those trees >28 m in height, did not differ significantly between nest patches and random patches (Figure 4; Z = –1.4, P = 0.14) even though a greater proportion of nest patches (71%) than random patches (37%) were classified as Very High. Tree height and large trees interpreted from airphotos, and occurrence of large trees assessed by the aerial survey method, were all significantly intercorrelated with each other (Tables 2 and 3). Combined, all the results regarding large trees indicated that nest patches often had more trees >28 m tall than did the random patches and that some of these trees will likely dominate above the main canopy of the forest.

The aerial survey method revealed significant differences between nest patches and random patches in terms of occurrence of trees with potential nest platforms (Figure 4; Z = –2.6, P = 0.009) and moss development—which was usually in the form of mossy pads—on these trees (Figure 4; Z = –2.6, P = 0.009). For both of these variables, nest patches were classified Moderate to Very High, whereas random patches occurred in all classes, with the highest proportions occurring in the Moderate and Low classes (Figure 4). Trees with platforms and moss development were highly correlated (Table 2) because, with the exception of one site, all sites were assigned the same classification. Tree height and large trees interpreted from airphotos were also correlated with trees with platforms and moss development as assessed by the aerial survey method; however, some of these correlations were relatively weak (Tables 2 and 3).

Classifying Habitat Quality

Habitat quality of nest patches did not differ significantly from that of random patches according to the airphoto interpretation method (Figure 5; Z = –1.6, P = 0.11). As determined by the aerial survey method, however, differences between nest patches and random patches were strongly significant (Figure 5; Z = –2.7, P = 0.007), while they were only marginally significant at the polygon level (Figure 5; Z = –1.8, P = 0.07). Generally, the airphoto interpretation method led to nest patches being classified in the upper four categories (Figure 5), while the aerial survey method led to nest patches being classified in the upper three categories (Figure 5). Regardless of the method, most nest patches were classified High or Very High, whereas random patches occurred across the range of classes, including Nil, by the aerial survey method (Figure 5).

The three different habitat quality variables (i.e., from the three methods) intercorrelated, and they correlated with the variables from which they derived (Tables 2 and 3). Based on the correlation values, tree height and canopy complexity appeared to have the strongest influences on the airphoto habitat quality classification (Table 2). Trees with platforms and moss development appeared to be the primary criteria for influencing the aerial survey habitat quality classification (Table 2).

Neither platforms of suitable diameter nor moss development—both of which are key elements for murrelet nesting—can be interpreted from airphotos. It is therefore important to identify which of the airphoto variables significantly correlate with the proportion of trees with platforms and moss development. As assessed by the airphoto interpretation method, tree height, large trees, canopy complexity, vertical complexity, and overall habitat quality all correlated significantly with platform trees. These variables also correlated significantly with moss development, with the exception of large trees which correlated only marginally (P = 0.06; Table 2). Small gaps on airphotos did not significantly correlate with platform trees or moss development (Table 3).

Comparison of Outcomes

Habitat quality of patches assessed by the airphoto method strongly correlated with that of patches assessed by the aerial survey method (Table 2). I.e., sites ranked high by the airphoto interpretation method were also ranked high by the aerial survey method. However, 71% of the 35 patches differed in the assigned habitat quality class. Classes assigned by the airphoto interpretation method appeared equally likely to be upgraded (37%) or downgraded (34%) by one class after the sites were assessed by the aerial survey method. Only 9% of sites differed by more than one class.

The ordinal logistic regression model (Appendix C) supported the notion that habitat quality assigned to a patch by the airphoto interpretation method may predict the class assigned to it by the aerial survey method (n = 35; Reduction of Deviance $\chi^2 = 18.25$, 4 df, $P < 0.001$; Table 4). Estimates resulting from the logistic regression model suggested that patches classified Moderate to Very High for habitat quality by the airphoto

Table 2. Spearman rank correlations comparing variables (n = 35), as estimated by the airphoto interpretation method and the aerial survey method. [a,b]

	Airphoto interpretation method			Aerial survey method					
Variable	**Canopy complexity**	**Vertical complexity**	**Habitat quality**	**Large trees**	**Trees with platforms**	**Moss develop.**	**Vertical complexity**	**Habitat quality patch**	**Habitat quality polygon**
Airphoto interpretation method									
Tree height	0.78	0.69	0.92	0.72	0.67	0.67	0.59	0.62	0.78
Canopy complexity	-	0.86	0.85	0.67	0.65	0.65	0.73	0.65	0.74
Vertical complexity		-	0.76	0.65	0.58	0.58	0.60	0.59	0.67
Habitat quality			-	0.77	0.69	0.69	0.55	0.65	0.82
Aerial survey method									
Large trees				-	0.57	0.58	0.45	0.57	0.69
Trees with platforms					-	1.00	0.53	0.97	0.91
Moss development						-	0.53	0.97	0.91
Vertical complexity							-	0.54	0.60
Habitat quality patch								-	0.90
Habitat quality polygon									-

[a] Significance ($P \leq 0.05$). [b] The significant correlations for meso slope, slope position, topographic complexity, and slope grade are reported in the text only.

Table 3. Significant associations among variables (n = 35) used in the airphoto interpretation method and the aerial survey method, using the Mantel–Haenszel statistic or the Cochran–Mantel–Haenszel Statistic.[a]

	Airphoto interpretation method			Aerial survey method
Variable	**Large trees**	**Small gaps**	**Crown closure**	**Canopy closure**
Airphoto interpretation method				
Large trees	-			
Small gaps	Not significant	-		
Crown closure	Not significant	**Significant**	-	Not significant
Canopy complexity	**Significant**	**Significant**	**Significant**	Not significant
Vertical complexity	**Significant**	Not significant	**Significant**	Not significant
Airphoto habitat quality	**Significant**	**Significant**	**Significant**	Not significant
Aerial survey method				
Large trees	**Significant**	**Significant**	Not significant	Not significant
Trees with platforms	**Significant**	Not significant	**Significant**	Not significant
Moss development	Not significant	Not significant	**Significant**	Not significant
Canopy closure	Not significant	**Significant**	Not significant	-
Vertical complexity	Not significant	**Significant**	Not significant	**Significant**
Aerial patch habitat quality	**Significant**	Not significant	**Significant**	Not significant
Aerial polygon habitat quality	**Significant**	Not significant	**Significant**	Not significant

[a] Significance ($P \leq 0.05$).

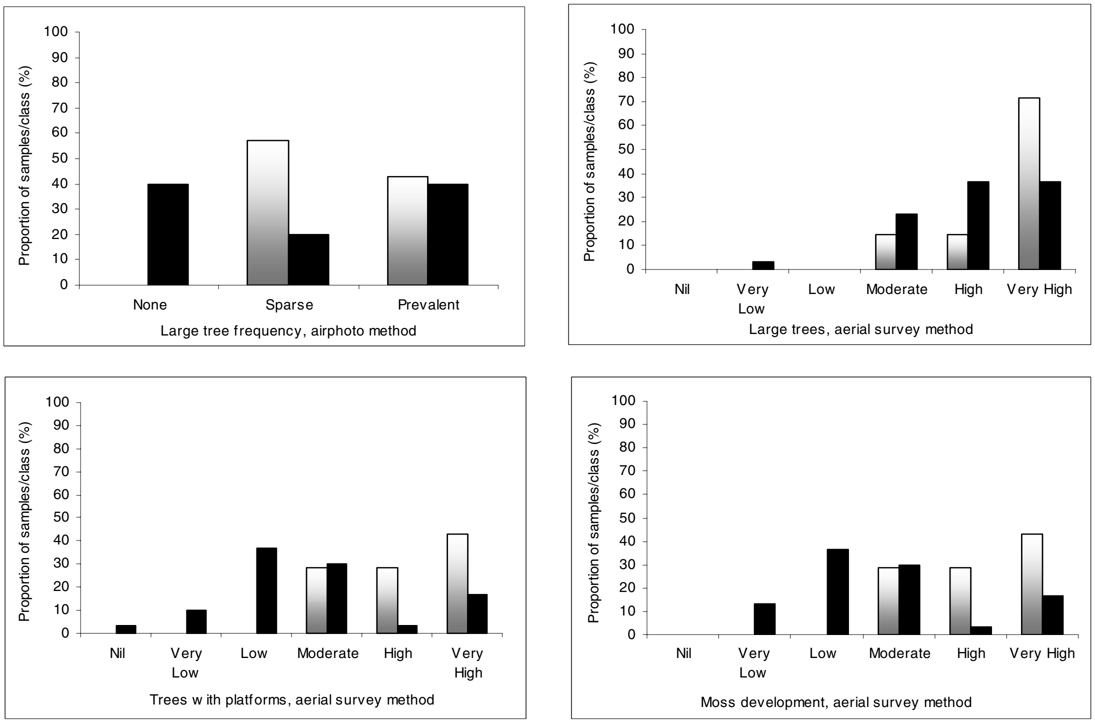

Figure 4. Comparison of nest patches (open histogram) and random patches (black), by class, using airphoto interpretation for the occurrence of large trees, and using aerial surveys for large trees, trees with platforms, and moss development.

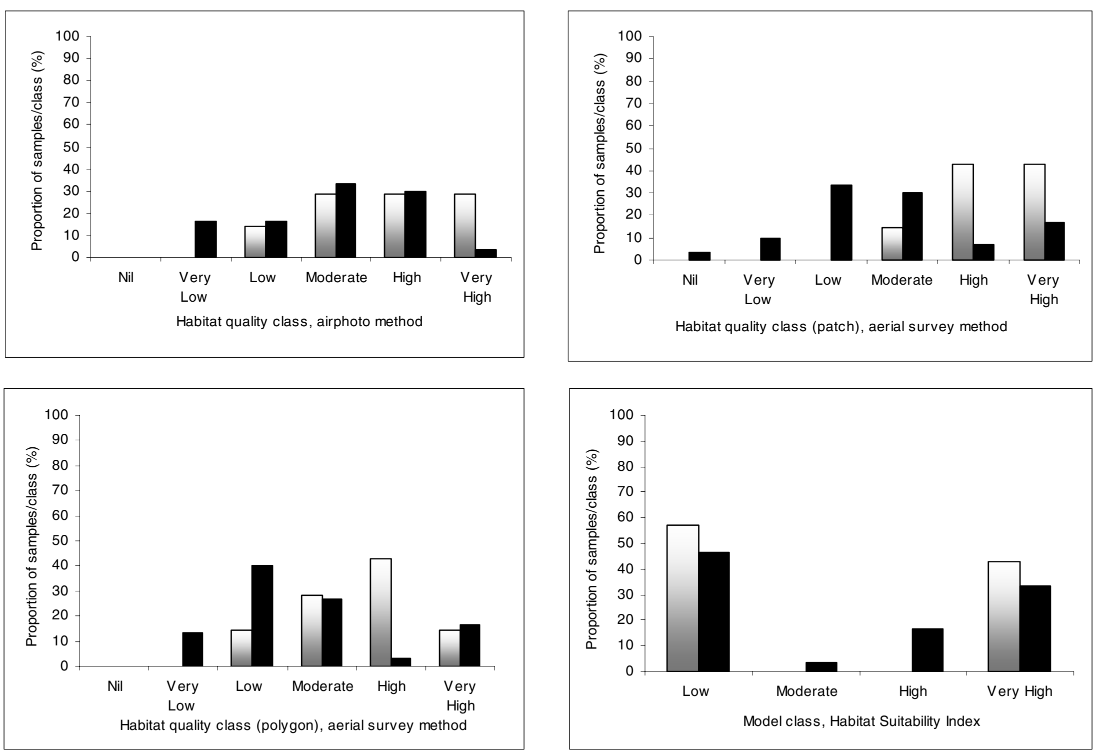

Figure 5. Comparison of nest patches (open histogram) and random patches (black), by overall habitat quality class, using airphoto interpretation of patches, using aerial surveys of patches and polygons, and using the GIS map-based habitat suitability algorithm.

Table 4. Parameter estimates from the ordinal logistic regression model (Appendix C) indicating the relationship that predicts aerial survey habitat quality class based on airphoto habitat quality class.[a]

Parameter	Estimate	Standard error
Intercept [1] α_1	-3.78	1.14
Intercept [2] α_2	-2.68	1.07
Intercept [3] α_3	-1	0.97
Intercept [4] α_4	0.90	0.97
Airphoto [Very High] β_1	4.66	1.68
Airphoto [High] β_2	3.15	1.19
Airphoto [Moderate] β_3	1.52	1.11
Airphoto [Low] β_4	-0.02	1.19

[a] Data from nest sites and random sites were pooled for this analysis (n = 35).

interpretation method tended to be classified similarly by the aerial survey method. Sites classified as Low by the airphoto interpretation method tended to class Very Low by the aerial survey method (Table 4). Both the raw data (proportions) and the predicted probabilities from the model (Tables 5 and 6) demonstrated this relationship between the two methods. Furthermore, sites classified as High by the airphoto interpretation method were more variable in their classifications relative to the aerial survey method (Tables 5 and 6).

Habitat quality of patches and polygons as assessed by the aerial survey method also correlated highly (Table 2). Yet, despite the correlation, 31% of the 35 sites were classified differently, with patch being classified higher than polygon for 26% of sites and the reverse for only 5%.

Significant differences between nest sites and random sites were not indicated using the GIS map-based habitat suitability algorithm (Figure 5). Both types of sites tended to be classified as either Very High or Low (Figure 5). The bimodal classification of sites produced by the algorithm was less reliable than either the airphoto interpretation method or the aerial survey method in differentiating nest habitat from other available forest in our study area.

Table 5. Likelihood of a sample in a particular habitat quality class determined by the airphoto interpretation method being classified in a particular class by the aerial survey method, using proportions.

Proportions	Aerial survey [Very High]	Aerial survey [High]	Aerial survey [Moderate]	Aerial survey [Low]	Aerial survey [Very Low]
Airphoto [Very High]	0.67	0.33	0.00	0.00	0.00
Airphoto [High]	0.45	0.09	0.27	0.18	0.00
Airphoto [Moderate]	0.00	0.27	0.36	0.27	0.09
Airphoto [Low]	0.00	0.00	0.33	0.33	0.33
Airphoto [Very Low]	0.00	0.00	0.25	0.50	0.25

Table 6. Likelihood of a sample in a particular habitat quality class determined by the airphoto interpretation method being classified in a particular class by the aerial survey method, using predicted probabilities.[a]

Predicted Probabilities	Aerial survey [Very High]	Aerial survey [High]	Aerial survey [Moderate]	Aerial survey [Low]	Aerial survey [Very Low]
Airphoto [Very High]	0.71	0.17	0.10	0.02	0.00
Airphoto [High]	0.35	0.27	0.28	0.09	0.02
Airphoto [Moderate]	0.09	0.14	0.39	0.29	0.08
Airphoto [Low]	0.02	0.04	0.20	0.44	0.30
Airphoto [Very Low]	0.02	0.04	0.20	0.44	0.29

[a] Predicted probabilities derived from the Proportional Odds logistic regression (Table 4).

DISCUSSION

Our results supported the notion that both the airphoto interpretation method and aerial survey method were useful for identifying the types of forest likely to be used by nesting Marbled Murrelets on the Queen Charlotte Islands/Haida Gwaii.

We recognize that our sample of nest sites was small and that a larger sample might reveal different trends; nevertheless, several trends concerning potential habitat use were indicated by the analyses. Such trends are useful preliminary guides for identifying and managing Marbled Murrelet nest habitat within the archipelago, and are also helpful in identifying patterns across the murrelet's range in British Columbia.

Studies similar to this one have recently been conducted on Marbled Murrelet nest sites in south coastal British Columbia; the study areas include the west side of Vancouver Island and the Sunshine Coast on the southern mainland (Waterhouse et al. in preparation; Waterhouse et al. in review). Hereafter, we refer to these studies as the south coast studies and, where possible, we compare our results to their results.

Describing Nesting Habitat

Elevation and Topography

We found that characteristics describing site location and topography were relatively poor indicators of potential Marbled Murrelet nest sites on the Queen Charlotte Islands/Haida Gwaii within forest >140 years old.

That murrelets select for lower elevation forests has been reported by researchers using direct measures (i.e., radio telemetry, Zharikov et al. 2006) and indirect measures (i.e., occupancy, reviewed by Burger 2002) of nesting activity. Therefore, we suspect the influence of elevation on murrelet habitat selectivity may be reduced on Queen Charlotte Islands/ Haida Gwaii because the elevational range of potential habitat (0 to 800 m) is generally narrower than that in south coastal British Columbia (up to 1500 m).

Findings differed for meso slope and macro slope relative to nest location position but this is not unexpected where they differ in scale of relative position. For example, a site could occur on a lower meso slope; while that meso slope is located in the Mid position on the macro slope. In other words, slope observed from a helicopter tends to describe the macro slope, where the position of the patch is relative to the gradient going from valley bottom to mountain top, or from and to major breaks in topography. Given that meso slope on airphotos is interpreted for the local water catchment area (3 to 300 m), it is usually describing only a portion of the same slope evaluated from the helicopter. Furthermore, the ability to interpret location on airphotos is influenced by scale of the photograph, available light, and any distortion at the edges of the photos. Interpreting slope position by the aerial survey method was likely influenced by the limited amount of time available to assess the patch.

Meso slope position and slope position (i.e., macro slope) may help determine where murrelets select habitat because slope influences productivity of the forest stand, and stands in more productive sites are more likely to have structures suitable for nesting, such as large trees with large-diameter branches. Sites that are water receiving, such as lower slopes, may have more productive forests than water shedding sites such as upper slopes. Furthermore, wind-exposed upper ridges may be less habitable because of climate (Meyer et al. 2004). The south coast studies suggested that murrelets selected lower meso slope position and slope positions (with some variance among study areas), while avoiding upper positions (Waterhouse et al. in review; Waterhouse et al. in prep.). A larger nest sample for the archipelago may in future support similar findings to those for the south coast. Ridge-top forests on the archipelago are comprised of smaller, stunted trees on relatively exposed bare-rock slopes. Productive forests on the archipelago usually occur on better-drained steeper slopes (usually mid) and flood plains (Green and Klinka 1994).

Consistent with the south coast, topographic complexity was not a significant predictor of murrelet habitat selectivity (Waterhouse et al. in review; Waterhouse et al. in prep.). Slope grade on the Queen Charlotte Islands/Haida Gwaii also did not differentiate nest patches from random patches because both mostly occurred on steep grades—and this likely reflects the general nature of the topography of the study area. On the south coast, slope grade was retained as a predictor of nest patch for a conditional Resource Selection Function. Nest patches were more likely to occur on steeper slope grades (Waterhouse et al. in prep.).

Forest Cover, Canopy Gaps, and Canopy Closure

Openings within or adjacent to a forest stand are thought to be associated with murrelet nest sites if the openings provide the birds with access to the forest canopy (Manley 1999). On the Queen Charlotte Islands/Haida Gwaii, most of the nest patches and random patches occurred in continuous forest >140 years old and all the patches lacked large gaps. Murrelets on the archipelago appeared to select for nest patches with a prevalence of small gaps. In contrast, nest patches in south coastal British Columbia were more often intersected by natural features, such as avalanche chutes, that created edges or large gaps, while occurrence of small gaps was more often sporadic in nest patches (Waterhouse et al. in review). We suspect that habitats with both large gaps and prevalent smaller gaps would be too open to provide adequate cover at nest sites, and murrelets may select habitat to balance openings for nest site access against cover for protection of the nest site (Waterhouse et al. in review). Therefore, for providing access into the stand, small gaps may be more prevalent in nest patches only on the archipelago because openings created by large gaps or edges associated with natural features are absent there.

Canopy closure better described nest patches than crown closure and may prove the more reliable of the two methods for describing murrelet habitat—keeping in mind they are assessed at different scales, with the aerial survey providing the closer view. But, the sensitivity of the crown closure and canopy cover estimates to the Canadian Marbled Murrelet Recovery Team (2003) classification leads us to suggest they are, as such, less reliable predictors of murrelet habitat and that they should be given less priority in assessing habitat quality. Neither proved good predictors of murrelet nesting habitat for the south coast studies (Waterhouse et al. in review; Waterhouse et al. in prep.)

Overstorey Canopy and Structural Complexity

Vertical complexity and canopy complexity determined by the airphoto interpretation method, and vertical complexity assessed by the aerial survey method, were useful indicators of nest habitat on the Queen Charlotte Islands/Haida Gwaii, with nest patches having greater vertical and horizontal forest structure. These variables may best provide information about habitat potential when they are considered in combination with other variables such as tree size and moss development.

Results from the south coast studies that used the airphoto interpretation method were similar to those of this study, with the exception that murrelets appeared to select against Non-Uniform forest on the south coast (Waterhouse et al. in review), while use of it by nesting murrelets was indicated on the archipelago. Murrelets may have avoided Non-Uniform stands in the south coast area for reasons similar to their selection of stands with fewer small gaps. I.e., Non-Uniform forests are characterized by more small gaps. On the archipelago, small gaps associated with Non-Uniform forests, may be more important for stand access.

Tree Height, Large Trees, Trees with Platforms, and Moss Development

Canopy or emergent trees with suitable nesting platforms are essential for nesting Marbled Murrelets (Nelson 1997; Manley 1999; Burger 2002; McShane et al. 2004). Our study confirms that both airphoto interpretation and aerial survey methods (Burger 2004; Donaldson 2004) provided information about tree structure that may help discriminate nesting habitat and its quality on the Queen Charlotte Islands/Haida Gwaii. The findings of this study were consistent with findings from the south coast studies (Waterhouse et al. in review; Waterhouse et al. in prep.). Tree height and occurrence of large trees as determined by the airphoto interpretation method, and occurrence of large trees, trees with platforms, and trees with mossy platforms (moss development) assessed by the aerial survey method, had some capacity for predicting murrelet nesting habitat in the south coast studies.

Yet, tree size based on height alone may not be sufficient to identify murrelet nesting habitat because some sites characterized by large trees >28 m in height lacked trees with platforms. For this study, occurrence of some larger trees relative to the canopy appears to be a key variable for assessing Marbled Murrelet nest patches by the airphoto interpretation method, while the availability of trees with mossy platforms (moss development) was one of the strongest features for distinguishing nest patches from random patches (Figure 3) by the aerial survey method. Some of the weaker correlations (Table 2) between tree size and other forest structure variables support the notion that the large tree variable alone may not prove a reliable indicator of habitat quality, and that trees with platforms and moss development should be considered when assessing Marbled Murrelet habitat quality.

Classifying Habitat Quality

Based on both the airphoto interpretation and aerial survey classifications, Marbled Murrelets on the Queen Charlotte Islands/Haida Gwaii tended to use nest patches classified as higher quality. These results were consistent with the south coast studies (Waterhouse et al. in review; Waterhouse et al. in prep.). Univariate analyses and correlations among the variables supported the general premise that although a range of sites are used by nesting murrelets, nest patches are more often associated with areas that have complex forest structure and higher densities of potential trees with nesting platforms. Although this knowledge increases our confidence in the airphoto interpretation and aerial survey classifications (Burger 2004), we suggest that information on individual variables be collected and retained, in addition to habitat quality class, until we better understand the contribution of each to the classification. For example, strong differences between nest patches and random patches were indicated based on availability of trees with platforms and moss development, and these variables may prove to be better predictors of quality than overall habitat class as determined by the aerial survey method.

Our data enabled us to make some assessment of the efficacy of the recommended approach for identifying and mapping the nesting habitat of Marbled Murrelets, which is to apply the three assessment methods—algorithm, airphoto interpretation, and aerial survey—in sequence (CMMRT 2003; B.C. Ministry Environment 2004).

Regarding the GIS map-based habitat suitability algorithm (McLennan et al. 2000), we have confirmed the conclusion reached by Manley et al. (2001) that the algorithm requires modification if it is intended to broadly define and detect potential suitable Marbled Murrelet habitat on the Queen Charlotte Islands/Haida Gwaii. Other algorithms may prove simpler and easier to apply (e.g., Hobbs 2003) but these also require verification using murrelet nest or detection data. Furthermore, the underlying forest cover mapping used by the algorithm may need improvement in terms of accuracy and minimum polygon size (i.e., conversion to Vegetation Resources Inventory Polygons, Vegetation Resources Inventory Committee 2002) before any algorithms can be applied and reliably identify murrelet habitat.

Our findings support using the airphoto interpretation method (Donaldson 2004) in conjunction with the aerial survey method (Burger et al. 2004). The aerial survey method served to narrow the range of habitat classes in which nest patches occurred, i.e., from the four uppermost within the airphoto classification to the three uppermost in the aerial classification. The improvement provided by the aerial surveys was in the confirmation of trees with platforms and moss development. Yet how the two standard methods are used in conjunction with one another in the future will depend partly on management objectives, funding limitations, and habitat quality thresholds.

Applying the Classifications

The following examples use the predicted probabilities derived from the ordinal logistic regression model (Appendix C) and demonstrate how the airphoto interpretation and aerial survey methods might be used in conjunction with each other to manage for murrelet habitat. We assume that the lower cost airphoto interpretation method precedes aerial surveys, that the predicted probabilities produced from our experiment using the 3-ha samples can be applied to larger areas of relatively homogenous forest, and that the current nesting habitat suitability thresholds on the Queen Charlotte Islands/Haida Gwaii are those in which nest sites have been located, i.e., Low to Very High on airphotos and Moderate to Very High by aerial surveys.

First, for operational planning, the predicted probabilities indicate which classes of stands interpreted by the airphoto method are more likely to require aerial surveying. In our study area, sites classified as Very High and High by the airphoto interpretation method were likely to be classified as Very High to Moderate by the aerial survey method. We therefore suggest that stands similarly classified do not require aerial surveying except to resolve a specific management issue or to confirm suitability as a Wildlife Habitat Area (B.C. Ministry of Environment 2004). But sites ranked Moderate, Low, or Very Low by the airphoto interpretation method would, on the same premise, require aerial surveying because aerial surveying would result in a small portion of the sites in each of these airphoto classes (e.g., ≤0.26, Table 6) being re-classified as either acceptable or unacceptable habitat (i.e., given the habitat threshold of Moderate).

Second, for strategic planning, the predicted probabilities might be used to adjust for the likelihood of overestimating or underestimating amounts of suitable habitat. If one wanted to estimate areas of suitable habitat using the airphoto interpretation method, then the predicted probabilities indicate how much habitat in each airphoto habitat quality class was potentially misclassified. The greatest risk in doing this is that some areas classified as higher quality may in fact lack the structures to support nesting murrelets. For example, although all habitat classified as Low by the airphoto interpretation method might be accepted as suitable nesting habitat (i.e., meets the current minimum suitability threshold), our results (Table 6) suggest that there is a 0.74 probability that a sample classified as Low by the airphoto interpretation method would either remain classified as Low or be reclassified as Very Low by the aerial survey method. These sites would therefore not meet the aerial survey method's minimum threshold for acceptable habitat, which is Moderate. In other words, using this example, in a landscape one might expect that of 1000 ha classified as Low suitability by the airphoto interpretation method, only 240 ha would potentially be re-classified as Moderate to Very High suitability after applying the aerial survey method—although one could not spatially identify the locations of this habitat on the airphotos.

MANAGEMENT IMPLICATIONS

Although our study focuses on the Queen Charlotte Islands/ Haida Gwaii, the general interpretations from our results are applicable throughout the murrelet's breeding range. Nevertheless, by contrasting our findings to the south coast studies, we also demonstrate that consideration must be given to how regional differences in ecosystems and disturbance patterns influence forest characteristics in particular habitats (Waterhouse et al. 2004).

Furthermore, the spatial scale of habitat assessment may influence site classification. Our comparison of patches and polygons from the aerial surveys suggested that the value of higher quality patches (approximately 3 ha) within stands may be underestimated by averaging across polygons of larger area (i.e., >3 ha). Pre-stratifying polygons by first using the airphoto standards may potentially help reduce this error, but we did not have this polygon information for this study. The spatial scales at which the airphoto interpretation and aerial survey methods are applied therefore need to be considered in assigning acceptable habitat class thresholds, because habitat selectivity described at the scale we examined may differ at the larger polygon scale. For example, if smaller patches of quality habitat tend not to be identified because the larger polygon estimate is an average, then a lower threshold may need to be used to ensure polygons with these patches of suitable habitat are identified. For the airphoto interpretation method, recording the occurrences of these patches as a separate index may help evaluate habitat quality of larger polygons (Waterhouse et al. in review). For the aerial survey method, more effort may be required to effectively survey larger polygons in terms of identifying smaller patches.

Identifying acceptable habitat quality based on airphoto interpretation or aerial surveys will likely always result in some portion of suitable habitat being rejected if the cut-off class is too high (Type I error), or it will result in unsuitable forest being accepted as habitat if the cut-off class is too low (Type II error). This is because murrelets use the range of habitat classes, although selectivity for higher quality classes is indicated. Approaches that land managers can use to deal with uncertainty in assigning thresholds include:

1. Use both the airphoto interpretation method and the aerial survey method to ensure that suitable nest habitat structure is present in stands assessed for murrelet habitat management.

2. When using lower habitat quality classes as management thresholds, set aside a larger area of forest in order to increase the probability that some acceptable habitat patches are included in these stands (Waterhouse et al. 2004).

3. When defining habitat using higher habitat quality classes for thresholds, ensure habitat is mapped at a fairly fine scale.

4. Ensure management goals recognize that some portion of the murrelet population will be nesting outside the area defined, mapped, and managed as habitat. If this outside area of lower classified "unmanaged" habitat is expected to help meet population goals, and if it has a high risk of becoming disturbed or made unavailable to murrelets, it will also need to be tracked and ultimately managed (i.e., invoke lower threshold or apply other management strategies).

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Appendix A. Airphoto interpretation method: variables described at 100-m radius plots (patches) centered on the murrelet nest sites and on random sites. Adapted from Waterhouse et al. (2004), Donaldson (2004), and Vegetation Resources Inventory Committee (2002).

Variable	Variable classes and definitions of classes
Forest cover >140 years old [a]	Proportion (%) of plot with forest >140 years old thought to provide potential nesting habitat.
Forest cover ≤140 years old [a]	Proportion (%) of plot with forest ≤140 years old, excluding non-vegetated and non-treed portions of plot.
Non-vegetated cover [a]	Proportion (%) of plot non-vegetated and non treed.
Vegetated cover [a]	Proportion (%) of plot vegetated but non-treed.
Tree height	Average estimated height (m) of the dominant, co-dominant, and high intermediate trees for the upper tree layer (Vegetation Resource Inventory 2002).
Large trees	Dominant trees with large crowns ≥5 m above the canopy of the main stand. **Prevalent**. >20% of stems are above main canopy. **Sporadic**. 3 to 20% of stems are above main canopy. **None**. <3% of stems are above main canopy.
Canopy complexity	Estimate of overall variability of canopy structure and the distribution and abundance of large crowns and canopy gaps created by local topography (e.g., slope, hummock, and streams), vertical complexity, and/or past stand disturbance (standing dead or down trees). **Very High/High**. Well-distributed big crowns and canopy gaps creating a heterogeneous horizontal layer; optimum crown closure typically 40 to 60%. **Moderate**. Fewer scattered large crowns. Varying numbers of canopy gaps, either well distributed or clumped, which result in greater variability in crown closures–typical range is 30 to 70%. **Low**. Few or poorly distributed visible large crowns and closed forest with few canopy gaps (usually high crown closure), or few large crowns but forest predominantly open (gappy, usually low crown closures).
Vertical complexity	Describes uniformity of the forest canopy by considering estimates of the total difference in height of leading species and average tree layer height. Three classes applied to the sample (Vegetation Resource Inventory 2002). **Uniform**. 11 to 20% height difference. **Moderately Uniform**. 21 to 30% height difference. **Non-Uniform**. 31 to 40% height difference.
Large gaps	Significantly visible openings (≥1 tree length wide) within the canopy. **Present**. Occupies ≥5% of plot. **None**. Occupies <5% of plot.
Small gaps	Smaller openings (<1 tree length wide) within the canopy. **None**. Gaps usually occupy <5% of plot. **Sporadic**. Gaps usually occupy 5 to 40% of plot. **Prevalent**. Gaps usually occupy >40% of plot.
Ranked crown closure	Follows recommendations of the Canadian Marbled Murrelet Recovery Team (2003). Percent estimate of the vertical projection of tree crowns (upper layer) upon the ground (Vegetation Resource Inventory 2002), classified as: **Most Likely**. 1 = 36 to 65%. **Moderately Likely**. 2 = 66 to 75% and 26 to 35%. **Least Likely**. 3 = <26% and >75%.
Meso slope	Relative position of plot within the local catchment area (~30 to 300 m vertical difference) (Luttermerding et al. 1990). **Low**. Lower-slope includes toe and flat. **Mid**. Mid slope. **Upper**. Upper slope.
Airphoto habitat quality	**Very High/High**. Forest >28 m tall and ≥250 years old. Includes: *Very High*. Abundant large trees and large crowns, and excellent canopy structure; best habitat in study area. *High*. Common and widespread large trees, very good canopy structure. **Moderate**. Forest usually 19.5 to 28 m tall and forest cover >140 years old, large trees with good crowns present but patchy distribution. **Low/Very Low.** Includes: *Low*. Forest generally >19.5 m tall or forest cover >140 years old, patchy and sparse large trees; poor canopy structure. *Very Low*. Stands generally <140 years old and <19.5 m tall, large trees and complex canopy structure are sparse or absent.

[a] From a measurement perspective the cover estimates are not independent variables, because they are dependent on one another with their composition adding to 100%. We opted to treat these estimates as independent because they are evaluated separately and transformations would complicate their interpretation. They are not combined for analyses.

Appendix B. Aerial survey method: variables described at 100-m radius plots (patches) centered on the murrelet nest sites and on random sites. Adapted from Burger 2004.

Variable	Description	Ranking
Large trees	% of canopy trees >28 m tall.	**Very High.** 51 to 100%. **High.** 26 to 50%. **Moderate.** 6 to 25%. **Low.** 1 to 5%. **Very Low.** ~1%. **Nil.**
Trees with platforms	% of canopy and emergent trees with potential nest platforms.	
Moss development	% canopy trees with obvious mossy platforms.	
Canopy cover	% cover of overstorey canopy based on vertical projection of crowns on the ground, using the recommendations from the Canadian Marbled Murrelet Recovery Team (2003).	**Most Likely.** 40 to 60%. **Moderately Likely.** 30 or 70%. **Least Likely.** <30%, >70%.
Vertical complexity	Gappiness and difference in tree heights, vertical complexity of the forest.	**Very High.** **High.** **Moderate.** **Low.**
Topographic complexity	Topographic features providing gaps and complexity to the forest (e.g., large boulders, rocky outcrops).	
Slope grade	Steepness of slope grade at site.	**Flat & Gentle.** **Moderate.** **Steep.**
Slope position	Position on slope.	**Low & Valley Bottom.** **Mid.** **Upper & Ridge.**
Aerial patch habitat quality	Overall habitat quality ranking of the 100-m-radius patch.	**Very High.** 51 to 100%. **High.** 26 to 50%. **Moderate.** 6 to 25%. **Low.** 1 to 5%. **Very Low.** ~1%. **Nil.**
Aerial polygon habitat quality	Overall habitat quality ranking of the polygon (which varied in area) surrounding and including the 100-m radius patch.	

Appendix C. Proportional odds logistic regression

The proportional odds logistic regression model can lead to greater power than other multi-category models, and is a straightforward extension of binary logistic regression.

The aerial survey classification of each observation, say Y_i , is restricted to one of five ordinal values, denoted for convenience by $k = 1,2,\ldots,5$ (i.e., Very High is indexed by 1, and Very Low is indexed by 5). The probability of falling into category k or less is modelled on the (cumulative) logit scale:

$$\text{logit}\left[P(Y_i \le k)\right] = \log\left(\frac{P(Y_i \le k)}{1 - P(Y_i \le k)}\right) = \alpha_k + \beta_1 d_{1i} + \beta_2 d_{2i} + \beta_3 d_{3i} + \beta_4 d_{4i} \quad k = 1,2,3,4$$

where

$\alpha_1, \alpha_2, \ldots, \alpha_4$	represent the unknown intercept parameters,
$\beta_1, \beta_2, \ldots, \beta_4$	represent the unknown regression parameters, and
$d_{1i}, d_{2i}, \ldots, d_{4i}$	are dummy variables (having a value of 1 or 0) that distinguish the five airphoto classification levels (the category Very Low is used as a reference).

Note that the final aerial survey class is not directly modelled because $P(Y_i \le 5) = 1$. Also, $P(Y_i = k) = P(Y_i \le k+1) - P(Y_i \le k)$.

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