The Reliability and Application of Methods Used to Predict Suitable Nesting Habitat for Marbled Murrelets

Discussion Paper

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Abstract

Identifying and mapping suitable nesting habitat within coastal forests is a key element in the recovery and management of the Marbled Murrelet (*Brachyramphus marmoratus*), which is listed as Threatened in Canada. This article reviews the reliability and application of three primary methods used to assess habitat suitability: the BC Model, a GIS-based algorithm using Vegetation Resources Inventory (VRI); air photo interpretation (API), direct assessments from air photos based on forest structure; and low-level aerial surveys (LLAS), helicopter surveys assessing forest canopy structure and the presence of potential nest platforms. In general, LLAS provides the most reliable identification and is the only method of the three that estimates the occurrence of potential nest platforms in the forest canopy. The other two methods, API and the BC Model, are substantially less reliable in identifying habitat actually used by nesting murrelets. Spatial scale and survey intensity affect habitat classification using all three methods. Generally, fine-scale (~3 ha), high-intensity classifications with LLAS and API are more likely to detect suitable habitat at known nest sites than those using medium-scale (10s or 100s ha) and/or low-intensity classifications. Even with fine-scale high-intensity application, 15% and 25% of known nest sites were still classified as "unsuitable" habitat with LLAS and API, respectively. All three methods applied at the medium scale for mapping appeared to miss fine-scale nesting habitat (i.e., small numbers of suitable trees occurring in otherwise unsuitable habitat). Areas of mapped suitable habitat can therefore be adjusted to take this discrepancy into account, and methods to do this are discussed.

KEYWORDS: Marbled Murrelet; *Brachyramphus*; habitat assessment; methodology

Introduction

The Marbled Murrelet (*Brachyramphus marmoratus*) is listed as "Threatened" (COSEWIC 2012) in Canada and is a "Schedule 1 species" under the federal Species at Risk Act (Species

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at Risk Public Registry 2012). The loss of nesting habitat in old seral forests is the primary reason for this listing, and recovery management of this seabird focuses on the retention of suitable forest nesting habitat (BC Government 2018, Environment Canada 2014). Critical habitat in the Marbled Murrelet recovery strategy (Environment Canada 2014: p. 22) is identified as "a state where greater than 70% of the 2002 suitable nesting habitat coast-wide remains." The 70% target refers to the entire British Columbia coast; regional adjustments are made to deal with past losses of habitat (see Environment Canada 2014 for details). Reliably identifying and mapping suitable nesting habitat in coastal forests is, therefore, a key element of the management of this species. Because murrelet nests are widely distributed in low densities, hard to find and not necessarily re-used every season (COSEWIC 2012), identifying nesting habitat is a challenging task.

This article assesses the reliability of the three primary methods used to identify and map Marbled Murrelet nesting habitat in British Columbia, and suggests how the methods might be best applied. The three methods are: the BC Model (Mather et al. 2010), a geographic information system (GIS)-based algorithm using 1:20,000-scale mapped forest-cover attributes and other GIS data; air photo interpretation (API) specifically designed to identify murrelet nest habitat using 1:10,000–1:15,000-scale photos (Donaldson 2004); and low-level aerial surveys (LLAS) of the forest canopy from a helicopter (Burger et al. 2004).

There have been previous reviews of aspects of these habitat-identification methods (Burger & Waterhouse 2009; Waterhouse et al. 2010). This new study provides updated and new technical data toward determining the reliability of each of the three methods. It first analyzes sets of known nest sites (located by radio tracking to avoid bias) and compares the proportions of these that fall within "suitable habitat" to proportions within "unsuitable habitat," as identified by each habitat classification and mapping method. Next, it draws on published studies and includes new analyses to compare the habitat classifications at sites that had both API and LLAS methods applied. This analysis shows how the spatial scale and survey intensity of habitat classification affects the success of each method in correctly identifying "suitable habitat," and how regional differences might apply to the mapping methods. The data analyzed here represent the most rigorous tests of these habitat classification methods possible, but there are limitations to their application (see the Discussion section), and practitioners of these methods are advised to refer to the original studies that are summarized here.

In most cases, LLAS would be the most expensive method to apply, given the high cost of helicopter time, but costs vary considerably due to variations in travel time, overlapping use of the helicopter (other work is sometimes undertaken at the same time as murrelet surveys), and the intensity of the survey method. Using API depends on the availability of recent high-quality air photos, and this too might incur additional flight costs to acquire suitable photos. A rigorous cost-benefit analysis of the three survey methods is therefore complex and beyond the scope of this review.

Methods

Regional variations

Regional variations in Marbled Murrelet habitat use and in factors that affect the development of potential nest platforms are known (Burger 2002, Burger et al. 2010). Data in this analysis came from four Marbled Murrelet Conservation Regions (Environment Canada 2014): Haida Gwaii, Central Mainland Coast, Southern Mainland Coast, and West and North Vancouver Island (Figure 1). No suitable data were available from three conservation regions: Alaska Border, Northern Mainland Coast, and East Vancouver Island.

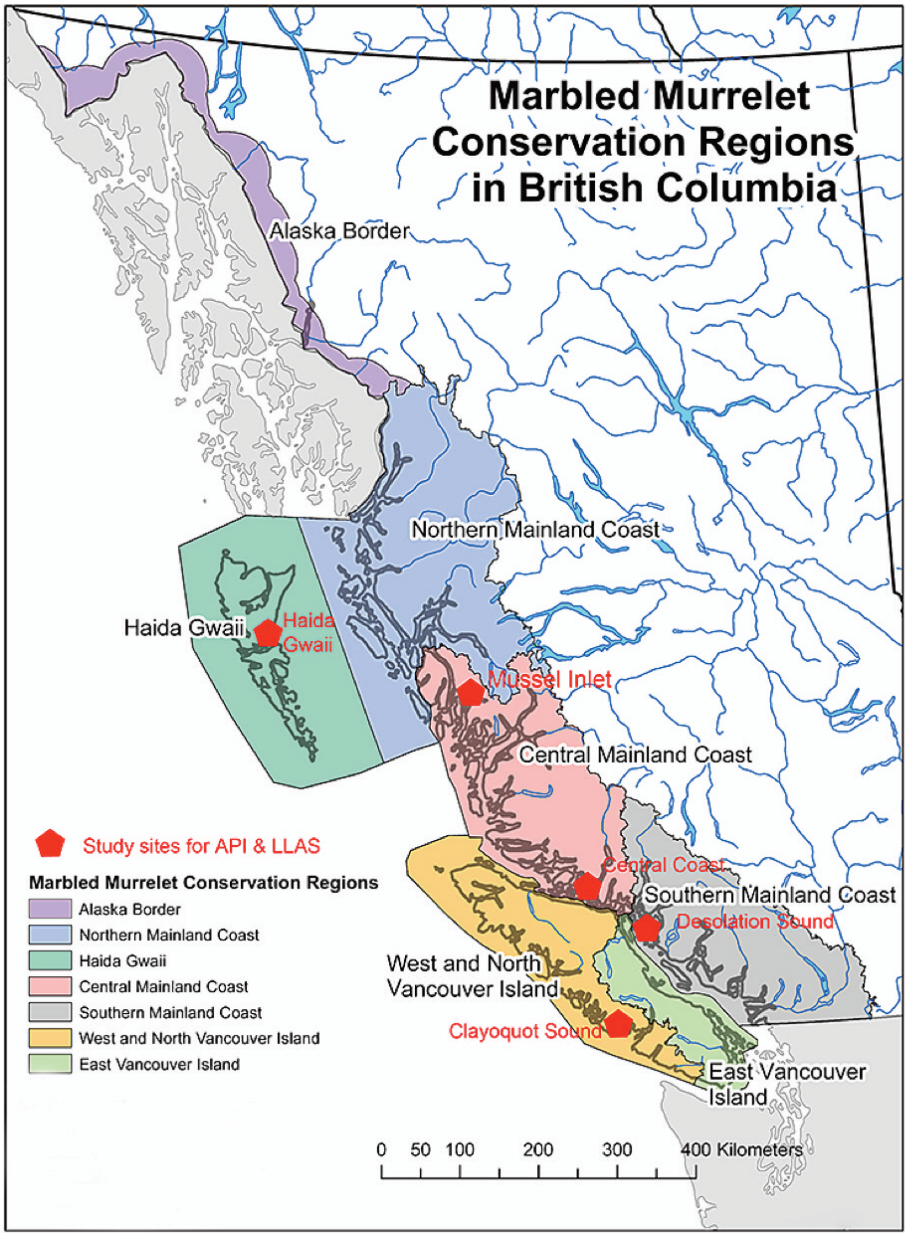

Figure 1. Map showing the seven Marbled Murrelet Conservation Regions within British Columbia and the locations of the studies testing air photo interpretation (API) and low-level aerial surveys (LLAS) used in this analysis. Map adapted from Environment Canada (2014).

Habitat identification methods, spatial scale, and survey intensity

The BC Model (Mather et al. 2010) was developed primarily for strategic planning across the entire British Columbian range of the murrelet, estimating the total habitat area and proportions within existing protected areas (e.g., COSEWIC 2012). It is a dichotomous model that ranks habitat as suitable or unsuitable. Most mapped habitat included in the BC Model was predicted by applying a GIS-based algorithm to 1:20,000-scale maps of Vegetation Resources Inventory data (VRI) (previously termed Forest Cover data) and using the estimated tree heights and ages combined with data on elevation and distance inland from potential marine foraging habitat. However, in three situations, the BC Model used mapped data other than VRI (Mather et al. 2010): Haida Gwaii was mapped with API (Cober et al. 2012), Clayoquot Sound was mapped using the Bahn and Newsom (2002) model, and private forest land (mainly in the East Vancouver Island conservation region) was mapped with Baseline Thematic Mapping.

The API and LLAS methods were designed for operational habitat identification; inventories and mapping are specifically focused on identifying key murrelet habitat attributes to classify the suitability of the forest as nesting habitat. Both API and LLAS have six quality classes ranked as Very High (1), High (2), Moderate (3), Low (4), Very Low (5), or Nil (6) (Burger 2004). In general, the top three classes (1–3) are considered to be "suitable" nesting habitat based on habitat-selectivity studies (reviewed in Burger and Waterhouse 2009). Class 6 (Nil) is, by definition, assessed to provide no likely nesting habitat (e.g., recent clear-cuts, wetlands, young regenerating forests, and rock). The published studies analyzed here explicitly avoided this category when testing API and LLAS methods (see the Results section).

Both the API and LLAS methods have been applied at two different spatial scales, and with two different survey intensities (Table 1). For mapping, the API and LLAS classifications are generally used in conjunction with 1:20,000-scale VRI data, producing medium-scale assessments of polygons usually 10s or 100s ha in size. This mapping involves assessing larger areas (e.g., Landscape Units) less intensely (Table 1). In addition, both API and LLAS have been used for verification studies of habitat maps and in research testing the classifications; in these cases, efforts focused on individual sites (i.e., fine-scale and high-intensity). These studies usually used plots (100-m radius, about 3 ha) centred on known nests or randomly-selected points. The surrounding polygons were usually also assessed to provide medium-scale comparisons with the fine-scale plot assessments. When LLAS is used for verification and research, more time is given to intensive scrutiny of the canopy microstructure; a helicopter hovers or circles slowly, allowing the observers to make an intensive search of the canopy for potential nest sites and other micro-habitat features (e.g., Cober et al. 2012, Donald et al. 2010, Waterhouse et al. 2007, 2009,). When LLAS is used for medium-scale mapping, the helicopter sweeps slowly across polygons, providing less opportunity for continuous fine-scale and intensive searching of the canopy micro-structure.

Table 1. The explanation of spatial scales and intensities of surveys for air photo interpretation (API) and low-level aerial surveys (LLAS) used to identify Marbled Murrelet nesting habitat in forests.

Differences in spatial scale (applies to both API and LLAS)	Fine-scale	Plots < 5 ha (generally ~3 ha; radius 100 m).
	Medium-scale	Polygons 5–10s to low 100s ha in area.
Differences in survey intensity (API)(generally correlated with spatial scale)	High-intensity	Applied to small research plots, < 5 ha, where more time is spent checking a smaller area than in medium-scale API.
	Low-intensity	Applied to larger polygons, > 5 ha, where each patch of forest gets less scrutiny than in fine-scale API.
Differences in survey intensity (LLAS)	High-intensity	An intensive search of forest canopy for potential platforms: a helicopter hovers or slowly circles for several minutes (generally ~5 minutes) around a point location or around a small polygon.
	Low-intensity	Helicopter sweeps slowly over a polygon with less time for continuous fine-scale and intensive searching of the canopy microstructure.

The data available for this study fell into three categories of LLAS application: fine-scale LLAS (which was always high-intensity plots), medium-scale high-intensity LLAS (polygons assessed in research and verification studies), and medium-scale low-intensity LLAS (larger polygons assessed for the habitat mapping of large areas). Similarly, there is differentiation between API fine-scale (applied to small plots) and API medium-scale (applied to larger polygons, assessed at lower intensity for mapping; Table 1). The BC Model data are, by default, at a medium scale (applied to larger polygons, assessed at lower intensity for mapping).

Analysis of nest distributions by habitat-identification method

The analyses used data from nests located with radiotelemetry (to avoid any search bias) from four locations (Figure 1): Desolation Sound, which includes Toba Inlet (*n* = 121 nests), Clayoquot Sound (*n* = 36), Mussel Inlet (*n* = 14), and Haida Gwaii (*n* = 7) (Simon Fraser University 2003, Waterhouse et al. 2007, 2008, 2009, 2011). Previous analyses by Burger & Waterhouse (2009) focused only on nests in forests more than 140 years old. The present analysis includes all the nests possible—including cliff nests and nests in forest less than 140 years old—that had been classified using API fine-scale and LLAS fine-scale plots, as well as new data from Mussel Inlet (Waterhouse et al. 2011). Sample sizes vary depending on the source dataset used; this is an unavoidable weakness in the cross-regional comparisons.

The distribution of nest sites among habitat classes by the three different methods is summarized at fine or medium spatial scales and by study area. The medium-scale summaries for all methods were made by directly overlaying the nest locations on the 1:20,000-scale maps produced by the BC Model (Mather et. al. 2010), and by API medium-scale and LLAS medium-scale low-intensity mapping (unpublished data from John Deal, Western Forest Products). Around each nest location, a 100-m radius buffer was placed to assess a standard fixed area and to help account for nest-site location accuracy. If the circular plot intersected suitable habitat on the map, it was classified as suitable, otherwise the site was classified as unsuitable. If the circular plot intersected API medium-scale- or LLAS medium-scale-ranked habitat, the highest-ranked habitat was selected.

Comparison of air photo interpretation and aerial survey methods

This comparison uses data from four locations (Figure 1) reported in three published and one unpublished source. The first source, Waterhouse et al. (2010), compared API fine-scale and LLAS fine-scale methods at 243 sites by pooling nests (*n* = 105) and randomly-selected points (*n* = 138) from Desolation Sound, Toba Inlet, and Clayoquot Sound. The second source, Cober et al. (2012), compared the habitat classifications on Haida Gwaii using fine-scale API plots and medium-scale API-mapped polygons with fine- and medium-scale high-intensity LLAS classifications of the same locations. These comparisons were made in five study areas at 190 API sites, including seven nest-site polygons and 183 randomly-selected polygons (20–55 randomly-selected sample sites per Classes 1–5; approximately 50 in four study areas and 12 in one study area). At each site, high-intensity LLAS classifications were made for both a fine-scale plot (100-m radius) and a polygon (usually up to a 20-ha area surrounding the plot), both centred on the API polygon. The third source, Donald et al. (2010), similarly undertook a verification study at seven Landscape Units on the Central Coast, comparing medium-scale API polygon classifications with medium-scale high-intensity LLAS polygon classifications. Tests were made at 332 randomly-selected API medium-scale polygons (approximately 50 sample sites per Classes 1–5; approximately 50 per Landscape Unit). Based on the results of the study, Donald et al. (2010) separated the Landscape Units into Group A (verification showed that API underestimated suitable habitat classes; 5 Landscape Units, *n* = 241 polygons) and Group B (verification showed that API overestimated suitable habitat classes; 2 Landscape Units, *n* = 91 polygons). Because Donald et al. (2010) found such marked differences in the performance of API in this region, and because they were able to partly explain these differences based on biogeoclimatic variations (which are summarized in the Discussion section below), this sub-regional analysis is included here. The fourth source is an unpublished GIS analysis (John Deal, Western Forest Products) that compared the matched proportions of mapped areas (hectares) by class from overlaying API and LLAS medium-scale low-intensity 1:20,000 maps for a subset of 11 Landscape Units on the Central Coast. The Landscape Units from the unpublished analysis have been divided into Group A (4 Landscape Units; n = 30,447 ha) and Group B (7 Landscape Units; n = 90,478 ha) as per Donald et al. (2010), but with hectares of habitat instead of numbers of polygons pooled for comparing the methods.

Results

Nest sites assessed by the various methods

Table 2 summarizes the numbers of nests within each habitat class, broken down by conservation region and spatial scale. In each sample, the number and percentage of nests that fall into "suitable" or "unsuitable" habitat is given. For the API and LLAS methods, which use the six-rank classification, suitable habitat is considered to be classes 1–3 (Very High, High, and Moderate). Some advantages and limitations of the methods emerge from these data.

Table 2. The distribution of known Marbled Murrelet nests in habitat classified as suitable (shaded) or unsuitable by the three methods of habitat classification.

A) BC Model map comparison (generally medium-scale, 1:20,000)

Location	Suitable	Not suitable	Total nests	% in suitable	% in unsuitable
Clayoquot Sound	25	11	36	69.4	30.6
Desolation Sound	63	58	121	52.1	47.9
Mussel Inlet	2	12	14	14.3	85.7
Total	**90**	**81**	**171**	**52.6**	**47.4**
Total excluding Mussel Inlet	88	69	157	56.1	43.9

B) Air photo interpretation (fine-scale, high-intensity, 100-m radius plots)

Location	Air photo - habitat class						Total nests	Suitable habitat = Class 1,2,3	% in suitable	% in unsuitable
	1	2	3	4	5	6				
Clayoquot Sound	0	16	10	5	1	2	34	26	76.5	23.5
Desolation Sound	7	44	27	8	11	2	99	78	78.8	21.2
Haida Gwaii	2	2	2	1	0	0	7	6	85.7	14.3
Mussel Inlet	0	0	6	5	1	1	13	6	46.2	53.8
Total	**9**	**62**	**45**	**19**	**13**	**5**	**153**	**116**	**75.8**	**24.2**

C) Air photo interpretation (medium-scale, low-intensity, 1:20,000)

Location	Air photo - habitat class						Total nests	Suitable habitat = Class 1,2,3	% in suitable	% in unsuitable
	1	2	3	4	5	6				
Haida Gwaii	1	2	1	3	0	0	7	4	57.1	42.9
Mussel Inlet	0	0	3	4	4	2	13	3	23.1	76.9

Table 2 (continued).

D) Low-level aerial surveys (fine-scale, high-intensity, 100-m radius plots)										
Location	Aerial survey - habitat class						Total nests	Suitable habitat = Class 1,2,3	% in suitable	% in unsuitable
	1	2	3	4	5	6				
Clayoquot Sound	7	15	6	2	1	2	33	28	84.8	15.2
Desolation Sound	38	27	15	8	3	4	95	80	84.2	15.8
Haida Gwaii	3	3	1	0	0	0	7	7	100.0	0.0
Total	**48**	**45**	**22**	**10**	**4**	**6**	**135**	**115**	**85.2**	**14.8**

E) Low-level aerial surveys (medium-scale, low-intensity, 1:20,000)										
Location	Aerial survey - habitat class						Total nests	Suitable habitat = Class 1,2,3	% in suitable	% in unsuitable
	1	2	3	4	5	6				
Desolation Sound	7	18	22	35	15	1	98	47	48.0	52.0

The BC Model applied in medium-scale coast-wide mapping showed a high proportion of nests (almost half) in “unsuitable” habitat (Table 2A). The BC Model showed strong regional variation: it included within suitable habitat 69% of nests at Clayoquot Sound, 52% at Desolation Sound, but only 14% of nests at Mussel Inlet.

Spatial scale is important for all methods: in general habitat classifications made at fine-scales (100-m radius plots) were more likely to show suitable habitat at nest sites than medium-scale classifications. When API focused on small plots (~3 ha; 100-m radius) 75.3% of nests (n = 154 nests) fell into suitable habitat, defined as Class 1–3 (Table 2B). When both Mussel Inlet and Haida Gwaii nests were assessed from medium-scale (1:20,000) API maps derived from air photo interpretation, the proportion falling into suitable habitat dropped compared to the air photo interpretation applied to small plots (compare Tables 2B and 2C). Caution is needed in interpreting these trends, because the sample sizes were small in both the Mussel Inlet and Haida Gwaii studies, and a change in one or two nests has a major change in the percentages (Waterhouse et al. 2011).

Fine-scale low-level aerial surveys done using research plots show the highest proportion of nests in suitable habitat: 85.2% of nests (n = 135) in Class 1–3 (Table 2D). No aerial surveys have been done at Mussel Inlet; descriptions from the original aerial search data suggest that some of the low-quality sites there would contain potential nest platforms, but in treed patches smaller than those interpreted in air photos or LLAS for 1:20,000-scale mapping (Waterhouse et al. 2011). Medium-scale low-intensity LLAS undertaken for nesting habitat conservation planning in Desolation Sound showed a much lower proportion of nests (47.5%) in suitable habitat than the fine-scale surveys (Table 2E). This value is similar to that using the BC Model map (52.1%; Table 2A).

The study examined whether nests in habitat ranked as “suitable” (Class 1–3) by fine-scale research surveys but missed in medium-scale mapping surveys fell within a wider range (Class 1–4) of mapping classes (Table 2). For Haida Gwaii, 100% of nests (n = 7; Table 2C) were captured in the suitable Classes 1–4 air photo (API) map, compared to 86% (n = 7; Table 2B) using the research plots ranked as Class 1–3. For Mussel Inlet, 58% of nests (n = 13; Table 2C) would be captured on the API map using Classes 1–4, which is similar to the 46% (n = 13; Table 2B) using the Class 1–3 research plots. For the Desolation Sound aerial (LLAS) mapping, 84% of the nests (n = 98; Table 2E) were captured in Classes 1–4, identical to 84% (n = 95; Table 2D) of nests captured in Class 1–3 using the research plots. Overall, the proportion of "suitable" nests in Classes 1–3 at the fine (research) scale is similar to the proportions of nests in Classes 1–4 at the medium (mapping) scale (either API or LLAS method).

Regional differences were evident with all methods (Table 2). The small sample of nests from Haida Gwaii was mostly (> 85%) classified as suitable habitat by all three methods at fine scales. Clayoquot Sound and Desolation Sound were intermediate for all three methods with 76–85% of nests classified as suitable using fine-scale air photo interpretation and aerial surveys. Medium-scale air photo interpretation (API maps) included more nests in suitable habitat on Haida Gwaii than at Mussel Inlet. The BC Model performed less well overall, and particularly at Desolation Sound. Mussel Inlet had by far the lowest correctly predicted habitat suitability with both fine-scale air photo interpretation and the BC Model (no fine-scale aerial surveys have been done there).

Comparison of aerial survey and air photo interpretation classifications

This section compares the habitat rankings made by API and LLAS at the same sites (Table 3). Fine-scaled analyses (Tables 3A and 3B) used both nest sites and randomly-selected 3-ha plots (see Waterhouse et al. 2010 and Cober et al. 2012 for details), whereas medium-scale analyses (Tables 3C–3G) used overlapping surveys in larger polygons (see the Methods section; Cober et al. 2012, Donald et al. 2010). As explained in the methods, the polygons surveyed in the Central Coast fell into two Landscape Unit categories: Group A and Group B (Tables 3D–3E and 3F–3G, respectively). In a six-scale classification system using observer-subjective criteria of very variable habitat, a perfect match between methods each time is not to be expected (there were exact matches at 29–55% of sites; Table 3). The two methods did, however, often classify habitat within one rank of each other (in all areas excluding Central Coast Group B Landscape Units 82–95% of sites were within 1 rank in API and LLAS classifications; within Central Coast Group B: 62–70%; Table 3).

Table 3. The comparison of habitat classifications made by air photo interpretation (API) and aerial surveys (LLAS) at sites assessed by both methods. The percentage of air photo classifications that fall into each aerial survey classification is shown*. Shaded cells show identical ranking.

		Air Photo (API) Ranking				
	Aerial Survey (LLAS) Ranking	1	2	3	4	5
A) Waterhouse et al. (2010): Desolation, Clayoquot, and Toba – fine-scale plots						
	1	69	52	11	0	0
Exact match: 47.5%	2	31	39	41	10	0
Within 1 rank: 95.0%	3	0	9	32	29	0
API overestimated by > 1 rank: 0.9%	4	0	0	11	43	45
API underestimated by > 1 rank: 4.1%	5	0	0	4	19	55
No. of plots		13	108	90	21	11
B) Cober et al. (2012): Haida Gwaii–fine-scale plots						
	1	60	40	2	3	0
Exact match: 45.2%	2	30	35	33	8	0
Within 1 rank: 90.0%	3	10	16	38	28	9
API overestimated by > 1 rank: 5.6%	4	0	7	18	39	37
API underestimated by > 1 rank: 4.4%	5	0	2	9	22	54
No. of plots		20	55	45	36	35

Table 3. (continued)

	Aerial Survey (LLAS) Ranking	Air Photo (API) Ranking 1	2	3	4	5
C) Cober et al. (2012): Haida Gwaii–medium-scale API polygons with medium-scale high-intensity LLAS						
	1	54	24	7	0	0
Exact match: 45.7%	2	35	41	20	6	0
Within 1 rank: 89.0%	3	12	25	41	26	9
API overestimated by > 1 rank: 6.6%	4	0	8	20	38	37
API underestimated by > 1 rank: 4.4%	5	0	2	11	29	54
No. of polygons		26	51	44	34	35
D) Donald et al. (2010) Central Coast–medium-scale API polygons with medium-scale high-intensity LLAS–GROUP A						
	1	65	23	4	0	0
Exact match: 54.6%	2	29	48	20	6	4
Within 1 rank: 93.8%	3	6	29	68	46	9
API overestimated by > 1 rank: 1.6%	4	0	0	6	34	29
API underestimated by > 1 rank: 4.6%	5	0	0	2	14	58
No. of polygons		48	48	50	50	45
E) John Deal analysis Central Coast–medium-scale API polygons with medium-scale low-intensity LLAS–GROUP A						
	1	50	23	7	2	1
Exact match: 37.1%	2	23	24	17	8	6
Within 1 rank: 82.2%	3	17	34	37	26	14
API overestimated by > 1 rank: 10.2%	4	9	14	34	50	55
API underestimated by > 1 rank: 7.6%	5	1	5	5	13	24
No. of hectares		482	2196	8570	6106	13,094
F) Donald et al. (2010) central coast–medium-scale API polygons with medium-scale high-intensity LLAS–GROUP B						
	1	16	0	0	0	0
Exact match: 39.3%	2	32	30	6	0	0
Within 1 rank: 69.7%	3	32	15	11	5	0
API overestimated by > 1 rank: 30.3%	4	16	30	39	40	0
API underestimated by > 1 rank: 0.0%	5	5	25	44	55	100
No. of polygons		19	20	18	20	14
G) John Deal analysis central coast–medium-scale API polygons with medium-scale low-intensity LLAS–GROUP B						
	1	2	2	1	0	0
Exact match: 29.0%	2	7	6	1	0	0
Within 1 rank: 62.4%	3	49	38	20	5	2
API overestimated by > 1 rank: 37.0%	4	41	47	37	30	12
API underestimated by > 1 rank: 0.6%	5	0	6	41	64	86
No. of hectares		366	2018	10,177	11,248	66,670

Note: To avoid bias resulting from unequal sampling across the API ranks, the % shown in this table (rather than the raw data) was used to calculate the proportions of exact matches, within 1 rank, and over- and under-estimates of API vs. LLAS rankings.

For comparisons that better matched management criteria, the data in Table 3 were condensed down to a comparison of "suitable habitat" (classes 1–3) and "unsuitable" (classes 4–5; there were no Class 6 sites); the results are in Table 4. Habitat classed as *suitable* by air photos (fine- and medium-scale) was generally also classed as suitable by aerial surveys (Tables 4A–4E), except for Group B of the Central Coast using API medium-scale (Tables 4F and 4G). Agreement between API and LLAS at the various scales and combinations of testing was lower for *unsuitable* habitat than for API-predicted *suitable* habitat, except for the Central Coast, Group B (Tables 4F and 4G). In the other comparisons 20–34% of sites classed as *unsuitable* by API (Class 4 and Class 5) were considered *suitable* when assessed using LLAS (Tables 4A–4E). This is generally interpreted as being due to the inability of air photos to show suitable potential nest platforms in the canopy, some of which might occur in marginal-looking trees.

Table 4. The comparison of habitat rankings made by air photo interpretation (API) and low-level aerial surveys (LLAS) with habitat grouped as Suitable (ranks 1–3 in Table 3) or Unsuitable (ranks 4–5). The percentage of air photo classifications that falls into each aerial survey classification is shown (sample sizes in Table 3). Shaded cells show matching ranking.

	Air Photo Ranking	
	Suitable	Unsuitable
A) Waterhouse et al. (2010) (Desolation, Clayoquot, and Toba)–fine-scale plots		
Aerial Surveys Suitable	93	25
Unsuitable	6	75
B) Cober et al. (2012) Haida Gwaii–fine-scale plots		
Aerial Surveys Suitable	86	24
Unsuitable	14	76
C) Cober et al. (2012) Haida Gwaii–medium-scale API polygons with medium-scale high-intensity LLAS		
Aerial Surveys Suitable	88	26
Unsuitable	12	74
D) Donald et al. (2010) Central Coast–medium-scale API polygons with medium-scale high-intensity LLAS–GROUP A		
Aerial Surveys Suitable	97	34
Unsuitable	3	66
E) John Deal analysis Central Coast–medium-scale API polygons with medium-scale low-intensity LLAS–GROUP A		
Aerial Surveys Suitable	66	26
Unsuitable	34	74
F) Donald et al. (2010) Central Coast–medium-scale API polygons with medium-scale high-intensity LLAS–GROUP B		
Aerial Surveys Suitable	47	3
Unsuitable	53	97
G) John Deal analysis Central Coast–medium-scale API polygons with medium-scale low-intensity LLAS–GROUP B		
Aerial Surveys Suitable	27	3
Unsuitable	73	97

On the Central Coast, unsuitable habitats in Group B were consistently predicted by both API and LLAS (97% agreement in both studies), but suitable habitats were not (27–47% agreement between methods; Tables 4F and 4G). Donald et al. (2010) reported that many of the Group B sites with poor agreement between methods were in hypermaritime forest (CWHvh1 or vh2 variants) and/or had low elevation and topographic relief and/or had forests subject to outflow winds. Proximity to the coast and/or wind is likely to affect moss development and the availability of potential nest platforms even in larger trees, but this is only evident following low-level aerial surveys. In other words, many stands with large trees in these Group B forests were ranked as suitable with API but, because they had few potential nest platforms, were ranked unsuitable with LLAS. This discrepancy between the methods applied to both high-intensity and low-intensity LLAS (Tables 4F and 4G, respectively).

Spatial scale did not show a strong effect on the agreement between API and LLAS if both methods were applied at the same scale. When pooled into suitable or unsuitable habitat, there is little difference among the results from fine and medium-scale assessments in Tables 4A–4D.

Survey intensity did affect the agreement between API and LLAS for habitat ranked *suitable* by API; the high-intensity LLAS polygon assessments done by Donald et al. (2010) on the Central Coast show higher agreement with suitable API than the low-intensity mapping LLAS reported from the same region by John Deal (compare Table 4D vs. 4E and Table 4F vs. 4G). This difference did not occur in the habitat ranked *unsuitable* by API; results were similar between the two levels of intensity for Central Coast Group A and identical for Group B.

Discussion

Caveats in the use of raw data

Table 2 summarizes raw data comparing the distribution of radiotelemetry nests located within habitat classified with different methods (BC Model, API, and LLAS), and Tables 3–4 compare the classifications of API and LLAS when applied to the same sites (plots or polygons). These data provide the most rigorous tests of the habitat classification methods that are possible at present, but there are limitations to their application due to sample sizes and study locations. The nest data come from comparatively few studies with limited geographical variation. For example, there are no known nest locations from the North Coast and few from the Central Coast (except Mussel Inlet), two regions that support large numbers of nesting murrelets (Environment Canada 2014) and where habitat classification appears to be most problematic, especially in the hypermaritime forests (based on the analyses by Donald et al. 2010). There are also few nests located with telemetry from Haida Gwaii, and the nests from Vancouver Island have limited distribution in and around Clayoquot Sound. Most nests are located at Desolation Sound, but this area is known to be highly modified by past timber harvesting, with about 80% of the original nesting habitat removed (Zharikov et al. 2006). The distribution of nests used in the remaining Desolation Sound habitat might not be typical for the species in less disturbed landscapes, such as Clayoquot Sound (Zharikov et al. 2007). Overall, therefore, there is not a fully representative sample of nest sites from across the British Columbia range, and nest samples are small in some regions. Furthermore, only three areas with nest sites have had medium-scale mapping and none of these have been mapped by all three methods, which limits comparisons among the methods using the nest data. The comparisons of API and LLAS classifications (Tables 3 and 4) do not rely on nest site locations, thus they cover a wider spatial range than the nest site analyses. But, these do not represent all the murrelet

Conservation Regions or the variability among likely habitats across the British Columbia range. All trends and conclusions arising from these data should therefore be viewed with caution.

The use of raw numbers has allowed the inclusion of all available data for both the nest comparisons (Table 2) and for the API vs. LLAS comparisons (Tables 3 and 4). Raw numbers do not, however, provide confidence limits for the trends that emerge. Probability modelling, as discussed below, gives an improved estimate, with confidence limits, of the likely availability of suitable habitat within each of the habitat classes.

Effects of spatial sale, survey intensity, and the source of data

Some general trends emerge from the data on the effects of spatial scale, survey intensity, and data source, and these three factors are intertwined. Overall LLAS surveys done at fine spatial scale (~3-ha plots) appear more reliable at detecting suitable habitat than LLAS undertaken at larger, polygon-level scales. Within polygon-level LLAS, surveys undertaken for verification and considered high-intensity might be more reliable than low-intensity LLAS surveys undertaken for the large-scale mapping of Landscape Units. This difference is probably because the low-intensity mapping LLAS is more likely to miss small patches of suitable habitat that occur within larger polygons of less suitable habitat (Waterhouse et al. 2007, 2010), or the high-quality patch is too small to raise the overall ranking of the polygon and is ignored (i.e., an averaging effect). Sources of data also seem important. In general, data derived from LLAS (which assess platform trees and stand structure directly) seem more reliable than data from API (which rely on 1:10,000–15,000-scale photos with polygons interpreted to describe murrelet habitat). Both LLAS and API outputs are more reliable than data from the BC Model (which relies on VRI forest-cover attributes primarily designed for estimating timber supply from air photos).

The differences in correspondence of ranking by API and LLAS found in two studies between Central Coast Group A and Group B (Tables 4D–4G) indicate that caution is needed in applying both methods. In the Group A sites, API and LLAS had similar levels of agreement on *suitable* habitat to those found in other areas outside the Central Coast, but somewhat higher differences in classifying *unsuitable* habitat. In Group B areas, by contrast, 53–73% of the sites rated *suitable* by API were found to be *unsuitable* with LLAS, a consequence of the paucity of potential nest platforms, even in large conifers. This was attributed by Donald et al. (2010) to the effects of oceanic winds inhibiting moss development in hypermaritime forests and strong winds having the same effect in some exposed inland slopes. Donald et al. (2010) report other substantial differences linked to Biogeoclimatic Ecosystem Classification (BEC) units in this study. Clearly, when applying these survey methods, the biogeoclimatic classifications (Pojar et al. 1987), wind exposure, and other factors affecting the development of potential nest platforms (Burger et al. 2010) need to be taken into account. In hypermaritime biogeoclimatic subzones or in areas strongly affected by wind or sea spray, practitioners must be aware that API is likely to overestimate habitat quality due to the paucity of suitable platforms, even on large, structurally suitable trees. Verification with fine-scale LLAS would reduce misclassifications.

The BC Model generally has modest success in predicting suitable habitat at the known nest sites. This seems due to spatial scale limitations (1:20,000 application), possible errors in the data source for tree height and stand age (derived from Forest Cover data for much of the British Columbia coast), and the application of elevation and tree-height limits (see the discussion in Waterhouse et al. 2010). The BC Model had higher success in predicting actual nest sites at Clayoquot Sound than in study areas where the model relied on VRI data. This might be attributed to the application of a more refined regional habitat model used in Clayoquot Sound (Bahn & Newsom 2002). Future versions of the BC Model might therefore become more reliable as VRI is updated. Both VRI and the BC Model might be improved further with the application of new technologies, such as Light Detection and Ranging (LiDAR), which is currently being tested for identifying and mapping Marbled Murrelet forest habitat (Clyde 2017, Hagar et al. 2014).

Applying habitat classification methods to identify candidate critical habitat

Critical habitat for the Marbled Murrelet in British Columbia is defined as 70% of suitable habitat existing coast wide in 2002, with regional adjustments (Environment Canada 2014). It is therefore essential to reliably identify and map the area of suitable habitat (i.e., the denominator from which the 70% will be drawn). The selection of such suitable habitat depends on the methods reviewed here. None of the currently used methods can solely provide a reliable map of suitable habitat across the murrelet's range in British Columbia. In addition, adjustments need to be made to the denominator area to account for nests not located in habitat identified as "suitable" by any of the current methods. The proportion of known nests falling outside mapped suitable habitat, even with fine-scale high-intensity LLAS, is sufficiently high (> 14% with all methods; Table 2) that some adjustments will likely be needed to achieve the recovery habitat targets (Environment Canada 2014).

In applying these methods to identify suitable habitat to meet the recovery goals (Environment Canada 2014), the provincial implementation plans (BC Government 2018), or local habitat management, the limitations outlined above need to be recognized. All three of the primary mapping methods (BC Model, low-intensity medium-scale LLAS, and medium-scale API) were likely to classify as "suitable" some habitat that is actually not suitable for nesting Marbled Murrelets, while excluding some that is suitable. The differences seen between Group A and Group B in the Central Coast data are a warning that general applications of API and LLAS classifications might not always be accurate, and there might need to be regional and subregional adjustments to the interpretation of the data. The errors inherent in all the mapping methods may be reduced at specific sites, and management boundaries may be adjusted when spatialized using fine-scale high-intensity LLAS (the most reliable indicator of actual nest habitat; Tables 2–4).

How to deal with nests that fall into "unsuitable" habitat?

Mapping based on medium-scale API mapping and medium-scale low-intensity LLAS shows that a high proportion of actual nests sites fall outside "suitable" habitat defined as —-3 (Tables 2D and 2F). Note that this outcome does not measure the extent of habitat selection by murrelets, which is defined as usage relative to availability (Manly et al. 2002). The analyses presented here address the simpler question of the classification of sites, and do not take into account the relative availabilities of different habitat classes, as has been done elsewhere (e.g., Waterhouse et al. 2007, 2008, 2009).

Data from fine-scale LLAS and high-intensity medium-scale LLAS suggest that these medium-scale polygon-level mapping surveys were likely missing or averaging out many of the small patches of suitable habitat that lie within larger polygons of unsuitable forest. Other research using these methods reached the same conclusions (Waterhouse et al. 2009, 2011, and references therein). This analysis shows that some nests within fine-scale Class 1–3 habitats, but missed by the medium-scale Class 1–3 mapping, do fall within mapped Class 4 habitat. How should Marbled Murrelet habitat managers deal with this unreliability, given the currently available maps? Three possibilities are discussed here: including medium-scale mapped Class 4 as suitable habitat; developing methods for estimating the proportion of Class 4 that is likely to be suitable; and excluding Class 4 but making adjustments for the proportion of nests that are likely to fall within Classes 4–6.

Including Class 4 as suitable habitat

Is it reasonable to include Class 4 from medium-scale mapping methods to capture a higher proportion of suitable stands? There are two major considerations here. First, including Class 4 habitat as suitable will add large areas of additional forest, much of it commercially viable, for consideration as candidate critical habitat. The proportion of potential habitat (Class 4 area divided by the total area of class 1–4) mapped by region varies from 10% (9,307 ha) in the Eastern Vancouver Island region to 48% (236,493 ha) for the North and Western Vancouver Island region; across the murrelet's British Columbia range there were over 880,000 ha of Class 4 habitat (Caslys Consulting, unpublished data from 2014). If 70% of this additional habitat becomes critical habitat, the economic impacts will be far greater than if only class 1–3 is included, with some adjustments made for nests likely to occur outside this habitat range (as suggested below).

Second, it is clear that Class 4 "suitable" habitat will include large areas that are not, in fact, suitable for Marbled Murrelet nesting. The proportion of the habitat within Class 4 polygons mapped by low-intensity medium-scale LLAS that is in fact small patches of Class 1–3 that were missed is not known. Very few nests are likely to occur in Class 4 if mapped at fine scales. If one considers the fine-scale LLAS as the most reliable method for assessing habitat, then the available data suggests that about 15% of nests fall outside of Class 1–3 (Table 2E). Some of these nests are known to be on cliffs and in patches of large trees within stands less than 140 years old (i.e., in Classes 5 or 6), so the actual portion within fine-scale Class 4 forest is less than 15%.

Overall, the inclusion of Class 4 as suitable habitat would therefore add large areas of additional forest for consideration as candidate critical habitat. This would have considerable economic impact, but most of this Class 4 habitat would likely be unsuitable, and therefore of no benefit to Marbled Murrelets. This approach is therefore not recommended.

Estimating the proportion of Class 4 that is actually suitable

The rationale here is to determine a biologically defensible proportion of Class 4 that is, in fact, suitable habitat and apply this proportion to determine an aspatial habitat area from Class 4 to include as the province-wide or regional denominator for candidate critical habitat. One approach is to apply predicted probabilities to estimate the proportion of misclassified mapped habitats, including the low-intensity medium-scale Class 4 habitat area (and other "unsuitable" classes) that is actually suitable for murrelets. This can involve verifying mapping quality using a more reliable assessment method and generating a matrix of probabilities (with calculated standard errors) of the occurrence of each class between the two methods. This approach, using LLAS to verify API maps, has been applied in the Central Coast (Donald et al. 2010) and on Haida Gwaii (Cober et al. 2012); consult these reports for the methodology.

For future operational planning, habitat currently classified as Class 4 can be reassessed using fine-scale LLAS (ideally coupled with fine-scale API), or by more refined methods, such as LiDAR, in order to identify those small areas within Class 4 that are, in fact, suitable and would be classed as 1–3 by these fine-scale methods when spatially mapped. The final estimate of candidate critical habitat can then be adjusted using the proportion of mapped Class 4 that the more reliable method indicates is actually suitable.

Another possibility is to consider the addition of the portion of Class 4 from low-intensity medium-scale LLAS mapping that is predicted to be suitable using the BC Model (i.e., look for non-overlapping areas considered suitable by two different mapping methods). Preliminary overlays suggested some Class 4 area overlapped the BC Model's "suitable" habitat area (John Deal, Western Forest Products, unpublished data); but because the BC Model also missed a substantial number of nests, as previously discussed, this correction is considered unreliable.

Adjustments for the proportion of nests found in unsuitable habitat

In areas where there are adequate samples of known nest sites, one can use the proportion of nests found in habitat classed as *unsuitable* by the mapping method (Classes 4–6) to estimate the additional area needed to be added to the mapped *suitable* habitat (Classes 1–3) to get a representative aspatial candidate critical habitat area. In addition to the nest locations, this method also requires estimates of the proportion of the study area that falls into each of the habitat classes. These data are then used to calculate the probability of usage of Classes 4–6 by nesting murrelets relative to the probability of usage in Classes 1–3. This relative ratio can then be applied to the estimated area of each class to get an aspatial estimate of the extra area needed to account for nests outside Classes 1–3. Burger et al. (2014) include a pilot application of this method for regions in British Columbia where there are adequate nest samples.

Conclusions

This review draws upon the significant research effort made over the past 25 years to understand and predict the nesting habitat used by Marbled Murrelets in British Columbia and how best to manage this habitat. Despite the years of research, there remain substantial gaps in our knowledge, especially since research has not been evenly spread across all the murrelet Conservation Regions in British Columbia. The regional differences that have been found suggest caution in applying results from one region to another. Both API and LLAS appear to be reliable in most situations, but this analysis confirms the conclusions of Donald et al. (2010) that API is less reliable in situations where local conditions inhibit platform development, such as some hypermaritime biogeoclimatic subzones and areas exposed to excessive wind or salt spray (Burger 2002, Burger et al. 2010).

While many of the data used above were derived from fine-scale assessments (often ~3 ha), and some of the telemetry nests were located within small patches of suitable trees (some < 1 ha in area), it should not be assumed that maintaining small patches of suitable forest in all situations is beneficial to Marbled Murrelets. Many other factors are applicable, such as the type of edge, the effects of disturbance near potential nest sites, desiccation, and the roles of buffers against edge predators and blow-downs (Malt & Lank 2007, 2009, Raphael et al. 2018, van Rooyen et al. 2011).

This analyses confirms that there are notable differences in the reliability of the three commonly used methods for identifying Marbled Murrelet nesting habitat in British Columbia. Previous reviews reported similar differences, but with fewer, more restricted data (Burger & Waterhouse 2009, Waterhouse et al. 2010). In general, LLAS provides the most reliable identification and is the only method of the three that estimates the occurrence of potential nest platforms in the forest canopy. Both API and the BC Model were less reliable in identifying habitat actually used by murrelets. But even with intensive, fine-scale LLAS, 15% of nests fell into habitat classified as unsuitable. The limitations of the three methods will need to be taken into account when they are applied, both with the spatially explicit selection of habitat at the landscape-unit level and at the aspatial regional scale, to identify critical habitat to meet the Marbled Murrelet recovery goals (BC Government 2018, Environment Canada 2014).

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