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Application of radar counts and forest cover GIS data to assess habitat associations of Marbled Murrelets breeding on southwest Vancouver Island

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ABSTRACT

We used high-frequency marine radar to estimate numbers of Marbled Murrelets (*Brachyramphus marmoratus*) entering 25 watersheds on southwest Vancouver Island, British Columbia in 2002-2005. We used counts of pre-sunrise incoming murrelets (heading into forest nesting habitat) as the most reliable count. The sum of the mean count was 3819 birds (N = 102 surveys at the 25 watersheds). Likely nesting habitat was mapped and estimated in GIS using a combination of forest cover data used for forest management, and satellite imagery identifying old coniferous forest and recent clearcuts. Estimating the likely catchment areas into which these birds were headed and where they might nest was difficult because of the topography; the absence of high mountains meant that murrelets were likely to fly over hills and low mountains from one watershed to another. Using the immediate watershed as the catchment area we found a significant correlation between murrelet counts and estimated area of habitat per watershed. Linear relationships were the most realistic fit to the data and explained 52.5% of the variation in mean murrelet counts, or 62.3% of the variation in the mean of the annual maximum count. Murrelet densities derived from these data were 0.080 and 0.092 birds per ha of likely habitat, for mean and mean of maximum counts, respectively. These mean densities were almost identical to those derived from previous studies covering 36 watersheds elsewhere on the west of Vancouver Island, but differed from those reported at 62 watersheds on the British Columbia mainland. Despite differences in local topography and degree of habitat loss southwest Vancouver Island therefore showed similar relationships between murrelet numbers and habitat availability as demonstrated elsewhere on the west of the island. Our data are useful for the management and conservation of this threatened seabird by identifying important breeding areas, establishing a baseline for future population monitoring using radar counts, and providing landscape-level habitat correlates and murrelet densities.

INTRODUCTION

Because of the difficulties in locating their nests, assessing the nesting habitat needs of Marbled Murrelets ((*Brachyramphus marmoratus*) has always been difficult (Ralph et al. 1995, Burger 2002, McShane et al. 2004). Active breeders are usually secretive, commute to and from nests in dawn and dusk twilight, and nests are high in the canopies of large old-growth conifers in coastal rain forests. The species is listed as Threatened in Canada and in Oregon, Washington and California, and loss of nesting habitat due to logging is the greatest cause for concern (Ralph et al. 1995, Nelson 1997). It is therefore important to identify watersheds in which large numbers of murrelets are nesting, to identify and predict the type of forest in which they are likely to nest, and to determine the areas of likely habitat needed to support local breeding populations.

High-frequency radar has recently been successfully applied in several studies to count Marbled Murrelets as they fly from the sea into their forest nesting habitat (Hamer et al. 1995, Burger 1997, 2001, Cooper et al. 2001, Cooper and Blaha 2002). Radar methods have been refined over the past decade, standard protocols now exist for this inventory method (Cooper and Hamer 2003, Manley et al. 2006), and radar counts have been identified as the most reliable method for long-term monitoring of murrelet populations (Arcese et al. submitted). When combined with measures of topography and forest cover in Geographic Information Systems (GIS), the radar counts also help to identify landscape-level habitat features important to murrelets as well as estimates of the densities of murrelets within those habitats (Burger 2001, Raphael et al. 2002, Burger et al. 2004). This information can then be applied in the management and conservation of the species (e.g., CMMRT 2003).

In this paper we report radar counts of murrelets and GIS habitat analyses made at 25 watersheds on southwest Vancouver Island, British Columbia over four seasons (2002-2005). This area supports one of the highest densities of nesting murrelets known in British Columbia and anywhere south of Alaska (Burger 1995, 2002). The goals of our study were: 1) to estimate numbers of murrelets using watersheds and hence identify key nesting areas for species in this important region; 2) to establish baseline radar counts for future long-term monitoring of murrelet populations; 3) to compare radar counts with GIS measures of forest structure and topography in order to identify relationships between habitat area and murrelet numbers per watershed; and 4) estimate densities (birds per ha of likely habitat) which could then be applied to determine areas needed to support target populations of breeding murrelets in this area. Our study complements similar radar studies undertaken nearby further north on the west coast of Vancouver Island (Burger 2001, Manley 2000), on northeast Vancouver Island (Harper et al. 2004), on the British Columbia mainland (Schroeder et al. 1999, Cullen 2002, Steventon and Holmes 2002), on Washington's Olympic Peninsula (Raphael et al. 2002), and by other incomplete studies in British Columbia.

STUDY AREA

Our study area on the southwest coast of Vancouver Island extended from Barkley Sound in the north to Port Renfrew in the south (Figure 1). This area provides a combination of productive nearshore foraging environment plus extensive stands of coastal coniferous old-growth in which the murrelets nest, and supports large populations of breeding Marbled Murrelets (Burger 1995, 2002).

The study area falls within the Coastal Western Hemlock (CWH) biogeoclimatic zone (Meidinger and Pojar 1991), dominated in our area by western hemlock (*Tsuga heterophylla*), western red-cedar (*Thuja plicata*), Sitka spruce (*Picea sitchensis*), and amabilis (Pacific silver) fir (*Abies amabilis*). This zone contains most of the coastal old-growth forest in British Columbia, and supports a substantial portion of murrelet's breeding population (Burger 2002). The study area included 3 variants of the CWH biogeoclimatic zone: CWHvh1 (very wet hyper-maritime) occurred at elevations below 150 m in forests exposed to open ocean; CWHvm1 (submontane very wet maritime) occurred from 0–600 m in sheltered inlets but from 150–600 m at exposed shores; CWHvm2 (montane very wet maritime) occurred from 600–900 m (Green and Klinka

1994). MHmm1 (windward moist maritime mountain hemlock variant) occurred sparsely as sub-alpine forests above 900 m.

Our study area included watersheds which are protected as parks (Carmanah, parts of Walbran), others which have experienced intensive logging over the past century (e.g., Sarita, San Juan) and others which have been more recently entered and in which there is ongoing clearcut logging and where important management decisions are being made (e.g., Klanawa, Toquart, Lucky Creek). Our study therefore provides capability for assessing future changes in both logged and protected drainages.

METHODS

Radar counts

We followed established methods for counting Marbled Murrelets with radar (Cooper and Hamer 2003, Manley et al. 2006) and used the same equipment as in previous studies (Burger 1997, 2001). We used a Furuno FR-810D 10 kW marine surveillance radar using 9410 MHz (X-band) transmitted through a tilted 2 m scanner. The scanner was mounted on the roof of a truck or, at sites with no road access, on a small sailboat. Observers had many years of murrelet radar experience (A.E.B., C.J.C, and B.K.S.) or were trained by us. Morning surveys began 90 minutes before sunrise and continued for 60 minutes after sunrise or 15 minutes after the last murrelet detection. Dusk surveys were undertaken to familiarize the observer with the local flight paths; the dusk survey data were archived but were not reported here. To reduce the possibility of counting the same birds twice, we restricted our analysis to counts of incoming (flying inland from the sea) murrelets recorded before the official sunrise (Burger 2001). We deleted any surveys in which rain or technical problems prevented surveys for more than 10 minutes of survey time during peak periods of murrelet activity.

Observers set the scanning radius at 1.5 km (0.75 nmiles) at most stations and at 1.0 km (0.5 nmiles) where the murrelets' flight path was well within 1.0 km. We turned off both rain and sea scatter suppressers and turned up the gain to near-maximum to give maximum sensitivity to the signals. Based on previous studies, Marbled Murrelets were identified on the radar screen on the basis of their image size, speed, flight-path and flight bearing (Burger 1997, 2001). A second observer, usually positioned about 50-100 m from the radar unit undertook a standard audio-visual (AV) survey for Marbled Murrelets, following the RIC (2001) protocol, and was also in radio-contact with the radar observer to report any birds (e.g., mergansers, pigeons) which might be confused with murrelets on the radar screen.

Full descriptions of each radar station are available from the authors , including written description, UTM location, map, and photos of the radar mounting and radar screen

GIS Analysis and Habitat Measures

We performed analyses on a 3 GHz desktop PC with dual processors using ARC/GIS 9.0. Seamless forest cover maps compiled from the Vegetation Resource Inventory (VRI) in the British Columbia government Data Warehouse (http://srmwww.gov.bc.ca/tib/vri/) were the main source of information on murrelet habitat. The maps were FC19 and FC20 for northwest and southeast Vancouver Island, respectively, as polygonal ARC export coverage in BC Albers83. Elevation data were derived from the digital elevation raster for the province of BC at 250 m pixel in BC Albers83, known as the Gridded DEM (http://srmwww.gov.bc.ca/bmgs/products/griddem.htm). We identified likely nesting habitat for Marbled Murrelets using the forest cover habitat predictors identified by the Canadian Marbled Murrelet Recovery Team (CMMRT 2003): age class 8 or higher (>140 years) and height class 4 or higher (>28.5 m tall). The forest cover databases had insufficient coverage to include other measures identified by the recovery team, such as canopy complexity and crown closure.

We discovered many gaps in the forest cover data and therefore applied a second measure of forest habitat. The Sierra Club of BC, working with the Wilderness Society, created a map of the ancient forests of Vancouver Island from Landsat MSS images in the early 1990's (http://staff.washington.edu/norheim/oldgrowth/whysodifferent.html)

This map was updated in 1999 and provided a continuous and uniform source of information on forest ages. Unlike the forest cover mapping, which is limited to administrative areas, this image covered the entire island with no gaps. The Sierra Club Ancient Forest map (1999) was a geo-referenced TIFF with 60 m pixels in UTM NAD27 Zone 10. The map is classified into 10 simple categories, of which we used the "Ancient Forest" option as the measure of likely murrelet habitat. The Sierra Club map was converted to BC Albers83 by using the ARCGIS projection tool to convert separately from UTM NAD27 to UTM NAD83, then from UTM to BC Albers. Displacement errors were corrected manually by shifting the reference points to match those of the forest cover maps.

In order to remove recently clearcut forest from the habitat map, we used an ortho-image of Vancouver Island created from 2003-2004 Landsat satellite imagery by Dr. Olaf Neimann (Dept. Geography, University of Victoria). A partially supervised classification using PCI Geomatica 8 (PCI Geomatics, Richmond Hill, ON) was used to identify recently logged areas. These areas were removed from the potential murrelet habitat determined from the VRI and Sierra Club maps. These corrections made the habitat map contemporary with the radar data.

We had no method to determine the ultimate destination of murrelets heading inland past radar stations (i.e., catchment areas), but following previous studies (summarised in Burger et al. 2004) we assumed that they were remaining within the drainage upstream of each radar station. Locations of watershed boundaries, lakes and streams were taken from the BC Watershed Atlas (http://www.bcfisheries.gov.bc.ca/fishinv/basemaps-watershed.html). This repository is derived from 1:50,000 lake and stream networks that have been aggregated into 3rd order and larger watersheds for fisheries management. These watersheds are a consistent and readily reproducible method of identifying contiguous areas of habitat that are upstream from radar stations. The areas of likely habitat within each watershed associated with a radar station were estimated by summarising the amount of habitat identified by the MMRT algorithm and the amount of Ancient Forest category on the Sierra Club satellite imagery map.

Comparison of radar counts with habitat measures

Once areas of likely habitat had been estimated within each of the 25 targeted watersheds, we compared this area with the number of murrelets seen to be entering each watershed. Because non-linear relationships had been detected in some radar studies (Northern British Columbia coast; Burger et al. 2004), we fitted a range of likely regression curves to determine the relationship between murrelet counts and habitat areas. To determine average densities (birds per ha of likely habitat) we calculated the arithmetic mean of the densities of the 25 watersheds, rather than use the slope of the count:habitat regression, because the regression was influenced by outliers. For statistical tests we used SPSS 13.0, with $P<0.05$ signifying significant differences. Means are presented with standard deviations (SD).

RESULTS

Radar counts of murrelets

Over four years we completed dawn surveys at 49 stations (Table 1). Of these, 14 stations were tested once, found to be unsuitable (targeted flight paths not reliably covered by the radar field), and were not re-surveyed. A further 7 stations provided reliable murrelet counts (useful for long-term monitoring) but the catchment area into which the murrelets were flying could not be reliably defined and they were not included in habitat analyses. The remaining 28 stations provided counts of murrelets entering 25 watersheds that could be reasonably well defined with GIS (Table 1, Figure 2). Some adjustments were necessary to accurately reflect numbers of murrelets entering some watersheds. Four watersheds had counts at two nearby stations which gave comparable results and data were pooled: stations at Nitinat River (Village NIT01 and Campsite NIT02) and Macktush Campsite (MAC01 and 02) had to be relocated to avoid conflicts with other human activities; two boat stations at Spencer Creek (SPE01 & 02) were sampled to test radar views and gave similar results; birds entering Henderson watershed were counted at both Uchucklesit (UCI01) and Useless Inlet (USE01). Finally, we tested four stations along Effingham Inlet trying to identify obvious flight paths into the Effingham drainage.

We found that murrelets entered the Effingham watershed via the estuary (covered by station EFI03) and a separate westerly route (covered by EFI04). Consequently we added 129 murrelets counted at EFI04 and heading into Effingham to the mean and maximum of three counts made at EFI03. Finally, Effingham Estuary (EFI03) allowed simultaneous counts of birds entering Effingham and Brand Creek watersheds. Total pre-sunrise murrelet counts (all flight paths) are summarised in Table 2. These data will be useful for future monitoring at these sites.

To compare numbers of murrelets with habitat variables we needed to focus on flight paths where birds appeared to be heading into specific watersheds. Defining the precise catchment area for each of these flight paths was sometimes difficult, but we began by identifying 25 watersheds into which we could see murrelets flying and where we could count these birds with reasonable accuracy (Table 3, Figure 2). At some of these watersheds (Effingham, Henderson, Macktush, Nitinat, San Juan, and Toquart) we used data from two nearby stations which both reliably sampled murrelets entering the watersheds (see methods). The sum of the counts at these stations was 3819 murrelets (4495 if we consider the mean of the annual maximum count), recorded in 102 surveys over the four years (Table 3).

Estimates of likely nesting habitat

Areas of likely nesting habitat within the 25 targeted watersheds were derived from the VRI data and using the Sierra Club "Ancient Forest" maps to fill in gaps in the VRI data (Table 4, Figure 3). The VRI forest cover data showed substantial gaps in all watersheds, indicating that habitat might be underestimated using these data alone (Table 4). Overall we identified 83,910 ha of likely nesting habitat. The proportion of each watershed that was considered to be likely habitat ranged from 14-73% and averaged 38% (Table 4).

Comparison of radar counts with habitat area

We found highly significant positive correlations between the counts of murrelets per watershed and the areas of habitat within the watershed; linear, quadratic and cubic relationships provided the best fit, but the differences in predictability (r^2 value) and shape of the curves were minimal for these regressions (Table 5, Figure 4). A power curve (which provided the best fit to comparable data from the north coast of British Columbia; Burger et al. 2004) was a poor fit for our data (Table 5, Figure 4). Consequently we assumed a linear relationship, which indicated that habitat area explained 52.5% of the variation in mean murrelet counts, or 62.3% of the variation in the mean of the annual maximum count (Table 5).

We also plotted the data using a regression forced through the origin, to create a more realistic situation where there would be no murrelets in watersheds with no habitat (Figure 5). This also allowed us to compare our data with the general trends determined from other studies on the west coast of Vancouver Island and the British Columbia mainland, which differed significantly from each other (Burger et al. 2005). Our data appeared to fit the former more closely (Figure 5).

Using each watershed as an independent measure, we estimated mean densities of 0.080 ± 0.079 (SD) and 0.092 ± 0.095 birds per ha of likely habitat using the annual mean and mean of the annual maximum counts respectively (Table 4). The high SD indicates the high degree of variance or scatter in these data.

DISCUSSION

Populations and monitoring of murrelets in study area

Our radar surveys confirm previous results from at-sea boat surveys (Sealy and Carter 1984, Burger 1995, 2002) which show that southwest Vancouver Island is one of the most important areas for breeding Marbled Murrelets in British Columbia. On average in 2002-2005 we counted 3819 murrelets (4495 if we consider the mean of the annual maximum counts) entering 25 watersheds in non-overlapping flight paths (our overall counts at all stations totaled over 6000 murrelets [Table 2], but these included several stations with overlapping flight paths). Since radar counts tend to underestimate actual numbers of commuting murrelets (Burger 2001) and we did not sample all the watersheds in the area, the overall total of murrelets within southwest Vancouver Island is likely to be about double this number. Watersheds with exceptionally high counts of murrelets and large areas of remaining habitat, which should be the focus for management priorities include: Toquart (437 murrelets; 4644 ha of habitat), Walbran (394 murrelets and 7569 ha in the upper valley alone), Henderson Lake valley (327 murrelets; 7048 ha)), San Juan (320 murrelets; 10,478 ha), Nitinat (312 murrelets; 7676 ha)), Lucky Creek (293 murrelets; 2004 ha), Klanawa (232 murrelets, 8012 ha in the east valley only), China Creek (216 murrelets, although we suspect most of these are heading well inland; 884 ha), Sarita (181 murrelets; 6100 ha), Gordon River (148 murrelets; 5957 ha), and Carmanah (115 murrelets; 5229 ha).

A comprehensive analysis of population monitoring of Marbled Murrelets in British Columbia concluded that radar inventory at selected watersheds was the most powerful method for tracking changes in local populations (Arcese et al. submitted). Such changes might be due to habitat loss from clearcut logging or to changes in the murrelets' foraging environment in the nearshore ocean, perhaps affected by global climate change. Arcese et al. (submitted) found that radar counts provided high power (>80-90%) to detect trends of -2% per yr within regions with 10-15 stations visited bi-annually for 10 years. Smaller declines should be detectable with greater survey effort, longer monitoring periods, or where historic data extend monitoring period. If regional populations share a common trend, data pooling may facilitate the detection of declines as small as -1% per yr. Our data from southwest Vancouver Island therefore provide essential baseline data for a large enough sample of stations to reliably track future changes in murrelet populations. Our sample of watersheds includes both protected and logged watersheds which will allow differentiation of the effects due to logging and/or changes in the marine environment.

Landscape-level habitat associations

We found significant positive correlations between numbers of murrelets per watershed and the areas of likely nesting habitat within these watersheds. Past studies have found similar positive relationships in two independent studies on Vancouver Island (Burger 2001, Manley 2000), three studies on mainland British Columbia (Schroeder et al. 1999, Cullen 2002, Steventon and Holmes 2002), and on the Olympic Peninsula, Washington (Raphael et al. 2002). These results suggest that populations of nesting murrelets are therefore determined by the area of available nesting habitat. The Clayoquot Sound study found evidence of reduced murrelet numbers in those watersheds in which 30-50% of the original habitat had been logged (Burger 2001).

The shape of the relationship between murrelet counts and habitat area gives some insight into how murrelets might respond to reductions in nesting habitat resulting from clearcut logging. Linear relationships suggest murrelet numbers should decline in proportion to the habitat loss, whereas strongly curvilinear relationships suggest that murrelets might crowd into the remaining reduced habitat in higher densities. Our analysis showed that only complex quadratic or cubic regressions fit the data better than linear regressions, and these complex regressions were little different from the linear trend (Figure 4). The curvilinear power curve, which did fit similar data from the north coast of British Columbia (Burger et al. 2004) was a poor fit to the southwest Vancouver Island data. Our results therefore support the contention (Burger 2001) that as nesting habitat is reduced by logging, murrelet numbers should decrease proportionately. Long-term monitoring of murrelet numbers in watersheds experiencing ongoing logging, using our established database, will provide a further test of this hypothesis.

Plots of our radar counts against habitat areas produced a wide scatter of points (Figures 4 and 5), although the trends were strongly significant. Part of the variability is due to difficulties in identifying the likely catchment areas into which murrelets recorded at a radar station were flying. In Clayoquot Sound (Burger 2001) and many other areas where such radar/habitat comparisons have been made (Raphael et al. 2002, Burger et al. 2004) catchment areas were often demarcated by barriers of high mountain ridges. Although some murrelets were known to cross ridges (Burger 2001, Burger et al. 2004, Harper et al. 2004) the proportion doing so is likely to be low where valleys are encircled by high mountains (>900 m). By contrast, most of our study area has only modest mountains with very few >900 m; consequently, defining the catchment areas and likely flight paths is difficult. Without doubt some of the outliers in our data were caused either by underestimating the areas into which the murrelets were flying (e.g. China Creek, Toquart and Lucky Creek, appearing as high points in Figures 4 and 5) or because the murrelets were entering the watershed via unsampled flight paths leading to underestimates of the numbers entering the watershed (e.g., Macktush, Handy, Franklin and possibly Klanawa watersheds, appearing as low points in these graphs).

Correctly identifying the appropriate catchment areas into which murrelets are flying, and where they might be nesting, remains one of the greatest challenges in linking radar counts of murrelets with habitat measures. Predictive models combining flight energetics, empirical data on commuting distances (Whitworth et al. 2000, Hull et al. 2001), the known distributions of nesting habitat (e.g., this study) and nest sites (e.g., Zharikov et al. 2006), are worth exploring but were beyond the scope of this study.

Densities of murrelets

Given the variability discussed above, estimates of densities (birds per ha of likely nesting habitat) are probably not reliable for individual watersheds, although the general trend across all watersheds is a useful measure. Applied with caution, such densities can be used to predict the areas of habitat needed to support targeted populations of murrelets, or conversely, the numbers of murrelets likely to be using specified areas of habitat can be predicted. Note that density as used here does not imply nest density since the relationship between the numbers of birds flying into a watershed and the numbers of pairs or nests within the area is not known. Radar counts include non-breeding birds and the proportion of breeding birds is likely to vary among years and through the season (Bradley at al. 2002, Peery et al. 2004). The same problem arises with counts of murrelets made from vessels at sea. In management and monitoring of Marbled Murrelet the population measure is therefore birds, including immatures, and not pairs or nests.

The mean density calculated from our data (0.092 birds per ha of likely habitat, using the mean of the annual maximum counts) closely matches the mean density derived using the same measure in previous studies on west Vancouver Island (0.090 ± 0.060 SD birds ha^{-1}; n = 36 watersheds), which differed significantly from the mean density on the British

Columbia mainland (0.045 ± 0.039; n = 62 watersheds; Burger et al. 2004). This result was not expected, because southwest Vancouver Island has much lower topographic relief and has experienced far greater habitat loss from logging than the other areas sampled further northwest on Vancouver Island (Burger 2002). The similarity means that the same mean density can be applied across all of west Vancouver Island with some confidence. Pooling our data with those summarised in Burger et al. (2004) gives a mean density (derived from mean of annual maximum counts) of 0.091 ± 0.076 SD birds ha^{-1} (n = 61 watersheds) for west Vancouver Island.

Management implications

Identifying the extent and distribution of likely nesting habitat for Marbled Murrelets is an essential first step in the management and conservation of this threatened species. This has proved to be difficult in British Columbia for several reasons. Algorithms which can be applied to forest cover GIS data at landscape-levels have not proven to be consistently reliable (reviewed by Tripp 2001, Burger 2002,). Furthermore, the current forest cover mapping incorporates many historical errors, often due to differences in methods across management units, and omissions, such as private land or parks that lack mapping. New forest cover mapping to consistent VRI standards probably won't occur for many years. Other sources of mapping habitat using satellite data are therefore needed. Our method of combining existing forest cover mapping with newer satellite imagery provides a valuable interim method for mapping and estimating areas of likely nesting habitat, which could be extended to generate a uniform and continuous coverage through the remaining range of the murrelet in British Columbia. The satellite interpretations which we used were aimed at identifying more general measures of old-growth forest. Interpretations of new satellite images made with the specific intention of identifying murrelet habitat could be even more successful.

Our data allow some priorities to be set for the maintenance of nesting habitats for Marbled Murrelet on southwest Vancouver Island. Our radar counts have identified watersheds which support large sub-populations of murrelets. Some of these watersheds are currently undergoing management reviews and our data are therefore important in the current management of these forests. We have already provided these data on the Henderson, Lucky Creek, and Toquart valleys to forest management authorities (BC Ministry of Environment, Nanaimo; BC Timber Sales) as part of the Arrowsmith Timber Supply Review covering these drainages. Our density estimates can be applied with reasonable confidence to estimate areas of habitat needed on the west of Vancouver Island to meet the recovery goals for this region being developed by the Canadian Marbled Murrelet Recovery Team (CMMRT 2003; Recovery Strategy in review). In the longer term we have laid the groundwork for ongoing population monitoring following the procedures recommended for British Columbia by Arcese et al. (submitted) and the Canadian Marbled Murrelet Recovery Team (CMMRT 2003).

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Table 1. Codes, names, target watersheds and UTM coordinates of radar stations sampled on southwest Vancouver Island, 2002-2005.This table includes some sites tested once but not deemed suitable for further surveys. At the other sampled stations some flight paths were deemed suitable for long-term monitoring or both monitoring and habitat analysis.

Station code	Station Name	Watershed for habitat analysis or monitoring	UTM coordinates (NAD 83 10U)	
			Easting	Northing
A) Stations suitable for monitoring and habitat analysis				
CAR01	Carmanah Point	Carmanah	371250	5385800
CAY01	Caycuse	Caycuse	376755	5405635
CHI02	China Creek Boat	China Creek	369514	5444930
DAR01	Darling River	Darling	351962	5399571
EFI03*	Effingham Estuary & Brand Creek	Brand Creek	339509	5439944
EFI03**	Effingham Estuary & Brand Creek	Effingham (count combined with EFI04)	339509	5439944
EFI04**	Effingham Inlet Bypass	Effingham (count combined with EFI03)	342125	5433550
FRB01	Franklin River Boat	Franklin	366172	5439227
GOR01	Gordon River	Gordon	396060	5380986
KLA01	Klanawa River	Klanawa - main river upstream of station	359200	5402247
KLA02	Gorge Creek	Gorge	356467	5404648
LUC01	Lucky Creek Boat	Lucky Creek	329650	5433000
MAC01 & 02**	Macktush Campsite	Macktush	366348	5440822
MAG01	Maggie Lake	Draw Creek	322076	5432324
NIT01 & 02**	Nitinat Village & Camp	Nitinat (including Big & Little Nitinat Rivers)	377002	5407534
NUM01	Numukamis Bay	Carnation Creek	352828	5419612
PAC01	Pachena Bay	Pachena	344876	5406668
PIP01	Pipestem Boat	Black Peaks Creek	336650	5433100
RIT01	Ritherdon	Ritherdon	354758	5424010
SAR01	Sarita Log Sort	Sarita (excluding Frederick Lake drainage)	350850	5416409
SJN01	San Juan Port Renfrew	San Juan River	395145	5378987
SPE01 & 02**	Spencer Creek Boat	Spencer Creek	360627	5426472
TOQ01	Toquart Log Sort	Toquart	327454	5432622

UCI01**	Uchucklesit Boat	Henderson (data pooled with USE01)	350250	5430950
USE01**	Useless Inlet Boat	Henderson (data pooled with UCI01)	350104	5428027
WAL03	Walbran (Mid Walbran)	Walbran & West Walbran (upstream of station)	381707	5388196
B) Stations suitable for long-term monitoring but not used for habitat analysis				
FCA01	Franklin Camp (3 flight paths)	North Coleman Creek and minor drainages	372679	5425874
FLK01	Francis Lake	Francis Creek and minor drainages	375318	5423838
HAT01	Nitinat Hatchery	Big & Little Nitinat Rivers	378610	5412986
KLA03	Bottard Creek	Bottard	352620	5403834
NAH02	Nahmint Lake	Upper Nahmint and cross-lake flights	350481	5449741
SOM01	Somass River	Somass	366296	5455522
SOM02	Alberni Quay	Somass	367800	5455180
C) Stations tested but not suitable for monitoring or habitat analysis				
BAM01	Bamfield at Marine Station	Trevor Channel	343199	5411296
CAR02	Carmanah/Bonilla Road	Carmanah	372917	5388479
CHI01	China Creek Campsite	China Creek	368909	5446034
COL01	Coleman Boat	Coleman	363150	5428650
EFI01	Effingham Inlet Boat #1	Effingham	342125	5433550
EFI02	Effingham Inlet Boat #2	Effingham	341760	5438740
HAN01	Handy Creek Boat	Handy Creek	357233	5426482
NAH01	Nahmint Bay Road	Nahmint	363319	5436581
NAH03	Nahmint Bay Boat	Nahmint	363306	5435657
SAR02	Sarita Lake	Upper Sarita	362555	5419169
SNO01	Snow Creek at Sproat Lake	Snow Creek	341355	5460203
SNO02	Snow Creek at highway	Snow Creek	342188	5460685
TOQ02	Toquart Boat	Toquart	329300	5434000
WAL02	Walbran (Bridge)	Walbran	382669	5389900

*At Effingham Estuary (EFI03) counts were made simultaneously for both Effingham and Brand Creek watersheds.
**Effingham, Macktush, Nitinat, Spencer and Henderson watersheds were all sampled at two separate stations (see text)

Table 2. Mean pre-sunrise counts of Marbled Murrelets at radar stations on southwest Vancouver Island. At many stations birds were recorded heading in more than one flight path; in these data all flight paths are pooled. Only stations with multiple surveys were included here, except those which could be combined with other neighbouring stations (Effingham, Toquart, Uchucklesit/Useless inlets).

		Annual mean count					No. of dawn surveys				
Station code	Station	2002	2003	2004	2005	All years	2002	2003	2004	2005	All years
CAR01	Carmanah Point	-	115	-	-	115	-	4	-	-	4
CAY01	Caycuse River	300	1045	-	-	548	2	1	-	-	3
CHI02	China Creek Boat	-	-	562	70	316	-	-	2	2	4
DAR01	Darling River	15	146	60	-	92	1	2	1	-	4
EFI01	Effingham Inlet Boat #1	-	183	-	162	173	-	1	-	1	2
EFI02	Effingham Inlet Boat #2	-	45	-	-	45	-	1	-	-	1
EFI03	Effingham Inlet Boat #3	-	-	71	12	51	-	-	2	1	3
EFI04	Effingham Inlet Boat #4	-	-	131	-	131	-	-	1	-	1
FCA01	Franklin Camp	-	-	43	23	33	-	-	2	2	4
FLK01	Francis Lake	-	-	31	-	31	-	-	2	-	2
FRB01	Franklin River Boat	-	-	59	38	48	-	-	2	2	4
GOR01	Gordon River	-	-	395	217	288	-	-	2	3	5
HAN01	Handy Creek	-	-	-	99	99	-	-	-	2	2
HAT01	Nitinat Hatchery	-	-	269	124	182	-	-	2	3	5
KLA01	Klanawa River	179	280	328	-	267	1	2	1	-	4
KLA02	Gorge Creek	67	157	190	-	152	1	2	2	-	5
KLA03	Bottard Creek	-	78	163	-	120	-	2	2	-	4
LUC01	Lucky Creek Boat	-	234	271	345	293	-	1	2	2	5
MAC01 &02	Macktush	2	2	-	0	1	1	1	-	2	4
MAG01	Maggie Lake	17	-	16	5	13	1	-	2	1	4
NAH02	Nahmint Lake	55	31	-	27	34	1	2	-	2	5
NIT01& 02	Nitinat River	254	385	559	174	312	2	2	1	2	7
NUM01	Numukamis Bay	-	-	79	58	68	-	-	2	2	4
PAC01	Pachena Bay	-	143	140	-	141	-	1	2	-	3
PIP01	Pipestem Inlet	-	78	39	-	59	-	1	1	-	2
RIT01	Ritherdon	-	-	211	173	185	-	-	1	2	3
SAR01	Sarita Log Sort	151	211	-	-	181	2	2	-	-	4
SJN01	San Juan Port Renfrew	-	-	457	184	320	-	-	2	2	4
SNO01 &02	Snow Creek	19	-	-	6	10	1	-	-	2	3
SOM02	Somass River	-	-	-	0	0	-	-	-	1	1
SPE01& 02	Spencer Creek	-	-	325	173	249	-	-	2	2	4
TOQ01	Toquart River	354	272	576	463	437	2	1	2	2	7
TOQ02	Toquart Boat	-	193	-	-	193	-	1	-	-	1
UCI01	Uchucklesit Inlet	-	279	436	212	315	-	1	2	2	5
USE01	Useless Inlet	-	-	386	-	386	-	-	1	-	1
WAL03	Walbran Mid	371	233	485	-	394	1	1	2	-	4
Total						6277					128

Table 3. Mean, standard deviation (SD), co-efficient of variation (CV), minimum and maximum pre-sunrise counts of incoming Marbled Murrelets entering 25 watersheds on southwest Vancouver Island in 2002-2005. The mean of each year's maximum count is also shown.

Watershed code	Watershed	Pre-sunrise count of murrelets: Mean	SD	CV	Min.	Max.	Mean of annual max.	No. of surveys
CAR	Carmanah Valley	114.5	61.0	53.2	63	196	196.0	4
CAY	Caycuse River	195.7	86.7	44.3	124	292	231.5	3
CHI	China Creek	215.7	227.5	105.5	62	477	292.5	3
DAR	Darling River	91.5	65.1	71.2	15	150	75.0	4
EFI	Effingham River	150.3*	-	-	-	173*	154.0*	4
EFI_BC	Brand Creek	29.7	25.1	84.6	6	56	31.0	3
FRB	Franklin River	35.3	1.0	2.7	34	36	36.0	4
GOR	Gordon River	148.2	99.4	67.1	47	287	244.5	5
HAN	Handy Creek	15.5	9.2	59.3	9	22	22.0	2
KLA_GO	Gorge Creek	151.8	76.1	50.1	67	234	175.0	5
KLA_KR	Klanawa River (excluding West Klanawa)	231.8	97.4	42.0	121	317	268.7	4
LUC	Lucky Creek	292.8	75.0	25.6	191	350	311.3	5
MAC	Macktush Creek	1.0	1.2	115.5	0	2	1.3	4
MAG	Draw Creek	13.3	11.6	87.7	3	28	16.7	4
NIT	Nitinat River (including Big & Little Nitinat)	311.9	157.3	50.4	96	559	396.3	7
NUM_CC	Carnation Creek	54.3	24.5	45.1	37	90	65.0	4
PAC	Pachena River	140.7	19.6	13.9	120	159	151.0	3
PIP_BP	Black Peaks	26.5	27.6	104.1	7	46	26.5	2
RIT	Ritherdon Creek	25.3	1.5	6.0	24	27	25.5	3
SAR	Sarita River	180.8	52.8	29.2	144	259	208.0	4
SJN	San Juan River	320.3	215.7	67.4	87	609	444.5	4
SPE	Spencer Creek	65.8	32.4	49.2	40	111	78.0	4
TOQ	Toquart River	436.9	129.7	29.7	272	636	458.3	7
UC_HEN	Henderson (Uchucklesit & Useless Inlets)	326.7	130.9	40.1	167	549	361.3	6
WAL	Mid & Upper Walbran Valley	393.5	125.7	32.0	233	532	378.7	4
Total		3819	-	-	1969	6024	4495	102
Mean		159.1		53.2			187.3	4.1

*Murrelets entered Effingham valley via two flight paths covered by stations EFI03 and EFI04; 129 birds from EFI04 were added to the means for EFI03 but SD and CV were therefore meaningless.

Table 4. Area of likely nesting habitat within each watershed as estimated using the Vegetation Resource Inventory (VRI) forest cover data and filling in gaps using the Sierra Club (SC) "Ancient Forest" algorithm. Densities of Marbled Murrelets derived from the radar counts (Table 3) are also shown.

Code	Watershed	Total watershed area (ha)	Areas of habitat (ha) as defined by: VRI	SC Ancient Forest	Total habitat area (ha)	Proportion which is habitat	Density (birds/ha) derived from: Mean radar count	Mean of annual maximum count
PIP_BP	Black Creek	624	290	100	391	0.63	0.068	0.068
EFI_BC	Brand Creek	1,124	364	148	512	0.46	0.058	0.061
CAR	Carmanah	6,724	2,989	2,240	5,229	0.78	0.022	0.037
NUM_CC	Carnation	1,013	349	16	365	0.36	0.149	0.178
CAY	Caycuse	19,111	5,325	645	5,970	0.31	0.033	0.039
CHI	China Creek	11,356	106	778	884	0.08	0.244	0.331
DAR	Darling	1,623	862	74	936	0.58	0.098	0.080
EFI	Effingham	6,051	1,429	1,062	2,491	0.41	0.060	0.062
FRB	Franklin	13,625	861	1,062	1,923	0.14	0.018	0.019
GOR	Gordon	30,772	3,641	2,316	5,957	0.19	0.025	0.041
KLA_GO	Gorge	2,290	1,353	34	1,388	0.61	0.109	0.126
HAN	Handy Creek	4,015	765	601	1,366	0.34	0.011	0.016
UC_HEN	Henderson	14,207	6,074	974	7,048	0.50	0.046	0.051
KLA_KR	Klanawa	15,256	7,564	448	8,012	0.53	0.029	0.034
LUC	Lucky	3,744	1,131	873	2,004	0.54	0.146	0.155
MAC	Macktush	2,814	1,075	161	1,236	0.44	0.001	0.001
MAG	Maggie/Draw	2,882	393	168	562	0.19	0.024	0.030
NIT	Nitinat	45,284	5,723	1,953	7,676	0.17	0.041	0.052
PAC	Pachena	4,923	533	166	699	0.14	0.201	0.216
RIT	Ritherdon	1,059	215	51	265	0.25	0.095	0.096
SJN	San Juan	66,961	6,692	3,786	10,478	0.16	0.031	0.042
SAR	Sarita	19,162	5,565	535	6,100	0.32	0.030	0.034
SPE	Spencer	1,129	184	21	205	0.18	0.321	0.381
TOQ	Toquart	10,211	2,643	2,001	4,644	0.45	0.094	0.099
WAL	Walbran	10,303	7,143	426	7,569	0.73	0.052	0.050
Total		296,263	63,272	20,638	83,910	-	-	-
Mean		11,851	2,531	826	3,356	0.38	0.080	0.092
SD		15,583	2,584	949	3,148	0.20	0.079	0.095

Table 5. Curve fitting for the relationship between numbers of Marbled Murrelet counted with radar and area of likely habitat within 25 watersheds on southwest Vancouver Island. Other curve types which had a poor fit to the data are not shown.

		Model Summary					Parameter Estimates			
Radar count	Equation	R Square	F	df1	df2	P	Constant	b1	b2	b3
Mean murrelet count										
	Linear	0.525	25.38	1	23	0.000	59.206	0.030		
	Quadratic	0.540	12.90	2	22	0.000	41.222	0.048	-2.1E-06	
	Cubic	0.544	8.35	3	21	0.001	25.777	0.072	-8E-06	3.76E-10
	Power	0.340	11.82	1	23	0.002	0.600	0.666		
Mean of annual maximum count										
	Linear	0.623	38.03	1	23	0.000	61.892	0.037		
	Quadratic	0.628	18.54	2	22	0.000	50.652	0.048	-1.3E-06	
	Cubic	0.637	12.30	3	21	0.000	24.264	0.090	-1.1E-05	6.43E-10
	Power	0.381	14.14	1	23	0.001	0.531	0.703		

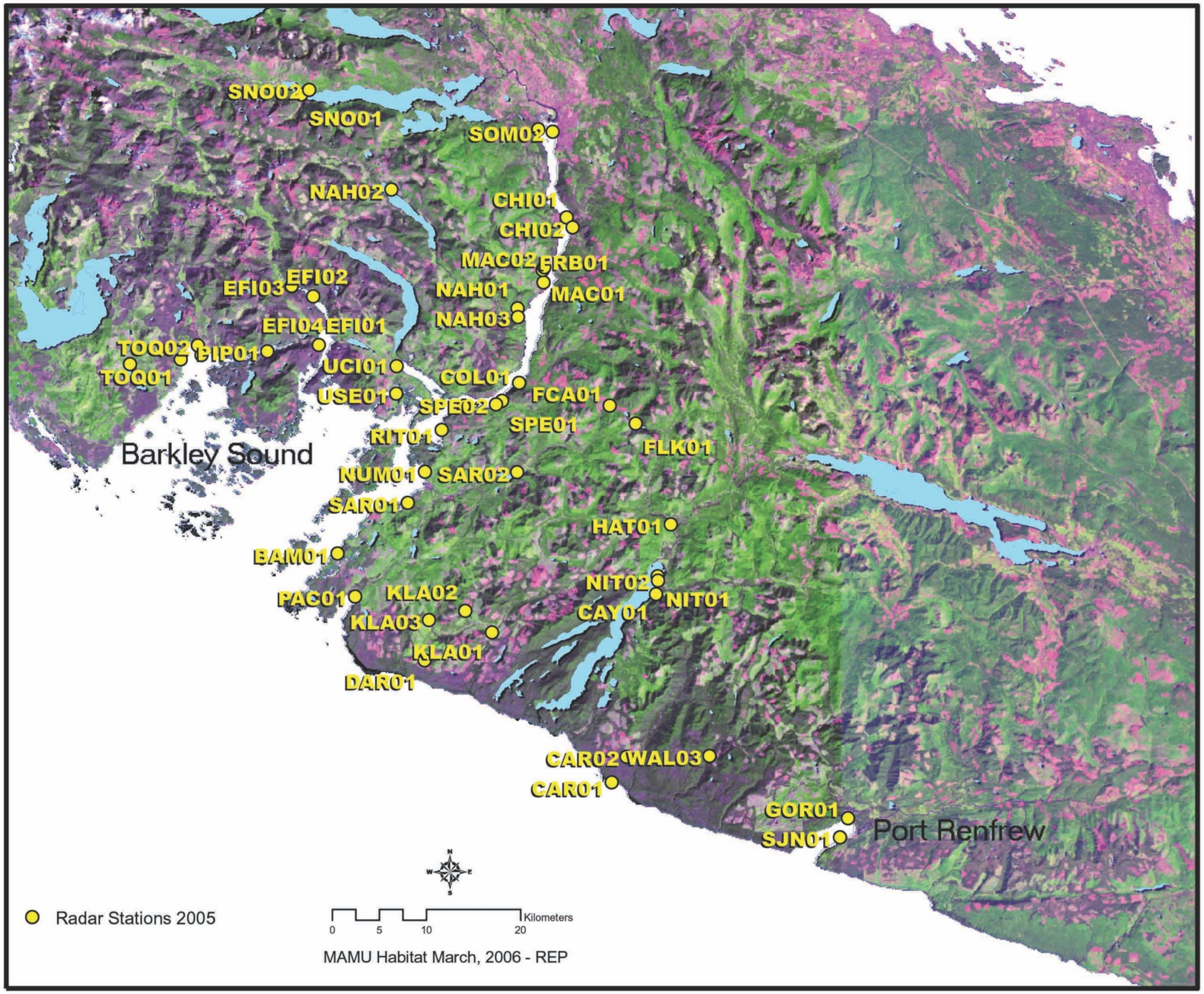


Figure 1. Map of the study area on southwest Vancouver Island showing the location of radar stations sampled in 2002-2005, superimposed on an orthophoto derived from 2003-2004 Landsat imagery (Dr. O. Niemann, UVic). Dark green areas represent old seral forests, much of which was likely nesting habitat for Marbled Murrelets..

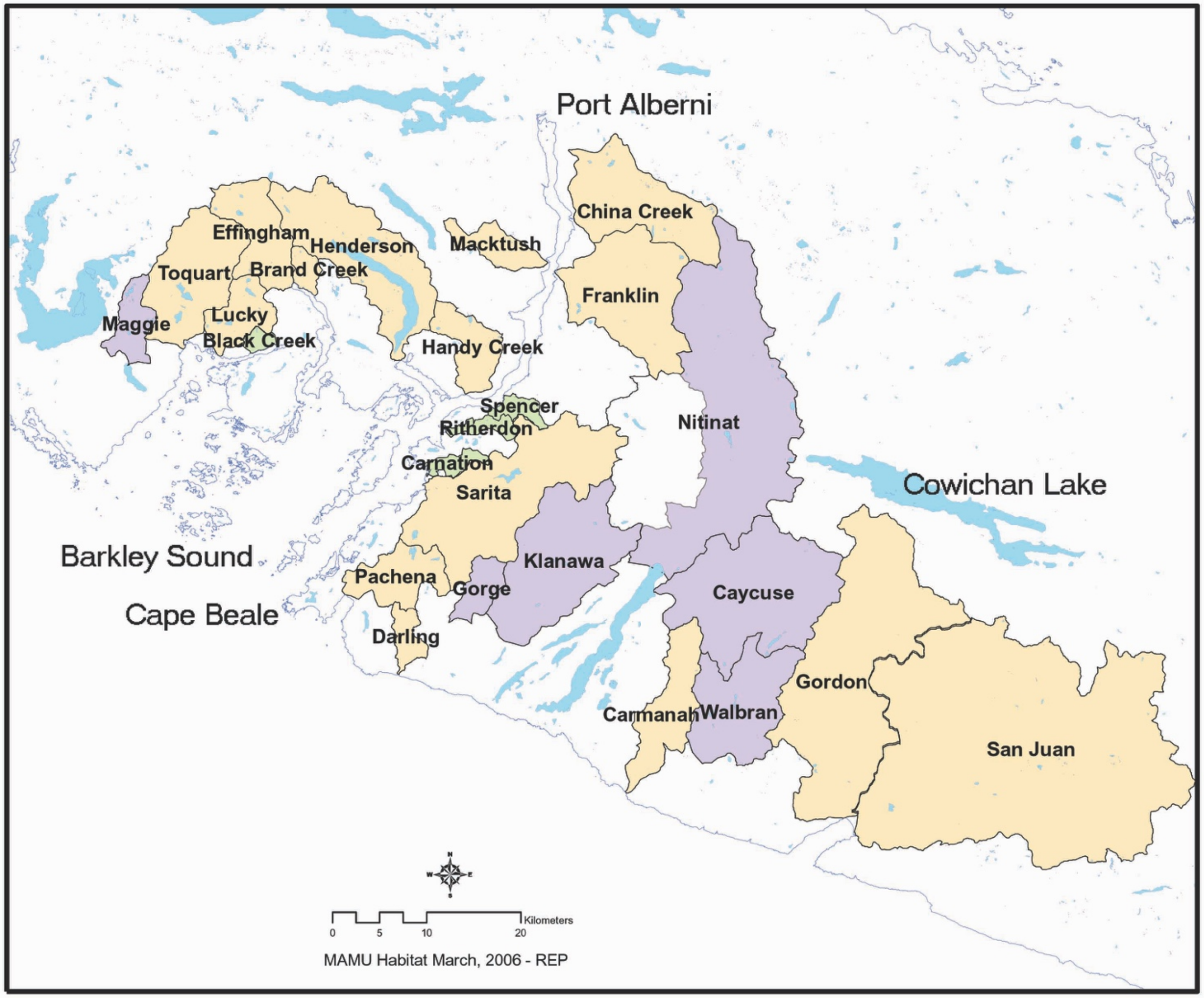


Figure 2. Location of the 25 watersheds used for comparing radar counts of Marbled Murrelets with areas of likely nesting habitat on southwest Vancouver Island. Watersheds coloured tan were derived directly from the British Columbia Watershed Atlas, those in purple were adjusted to remove portions which were not covered by the radar counts, and those in green were manually extracted from larger watersheds using GIS.

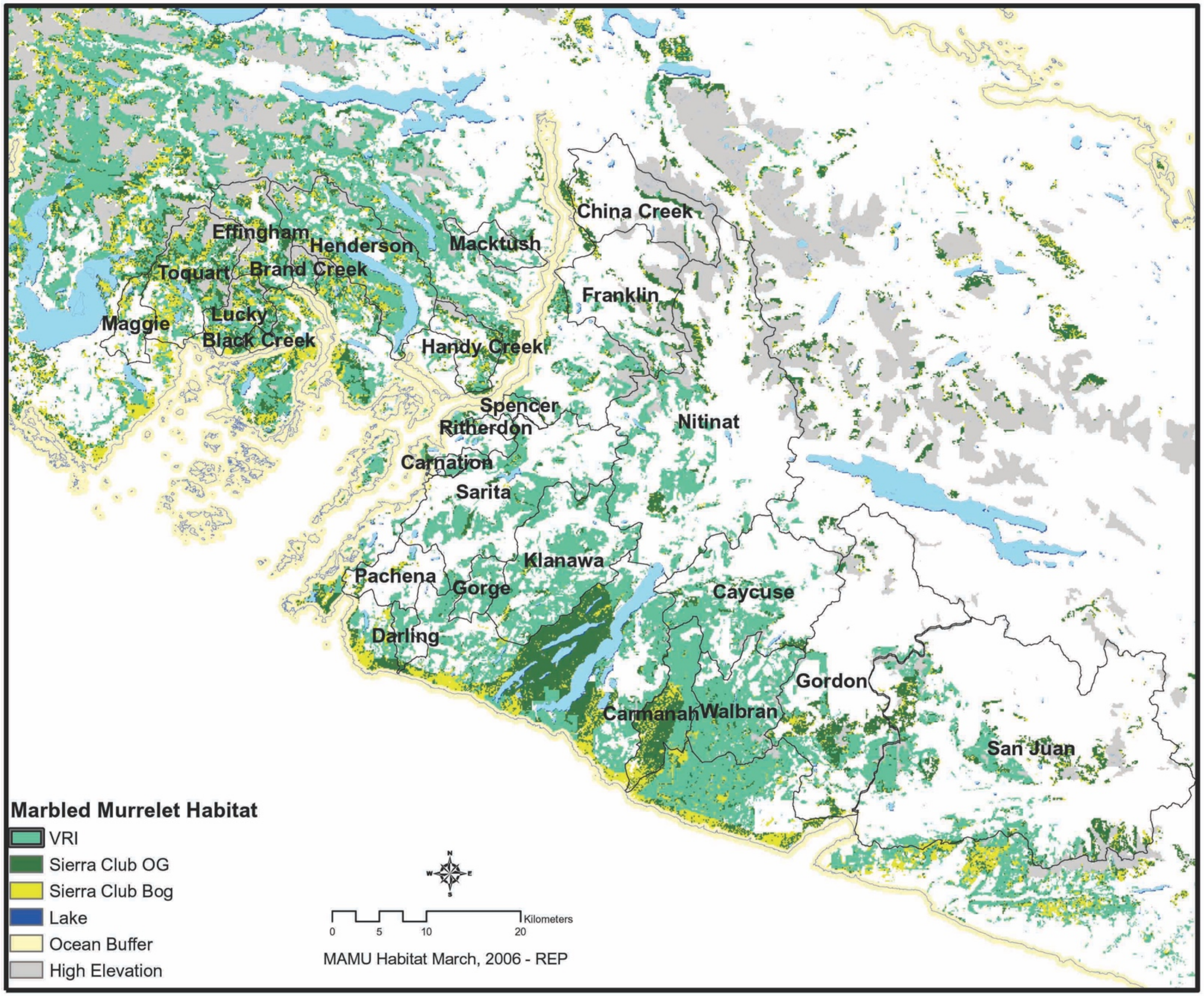
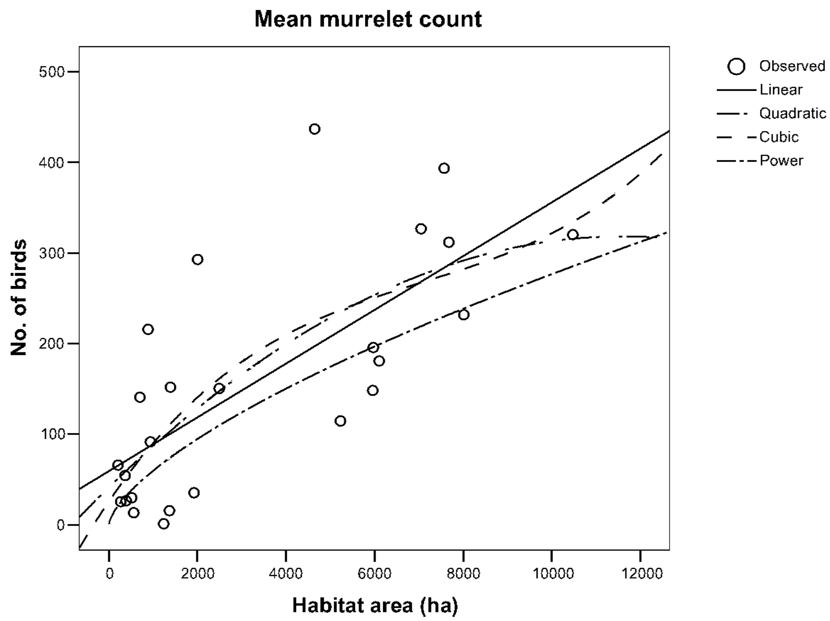


Figure 3. Map showing the extent of forest considered to be likely nesting habitat for Marbled Murrelets on southwest Vancouver Island. The habitat was mapped by applying the CMMRT (2003) algorithm (age class 8+, height class 4+) to forest cover data, or where these data were lacking, from the "Ancient Forest" definition of the Sierra Club satellite imagery analysis. Areas of recent logging determined from satellite imagery were removed (see methods).



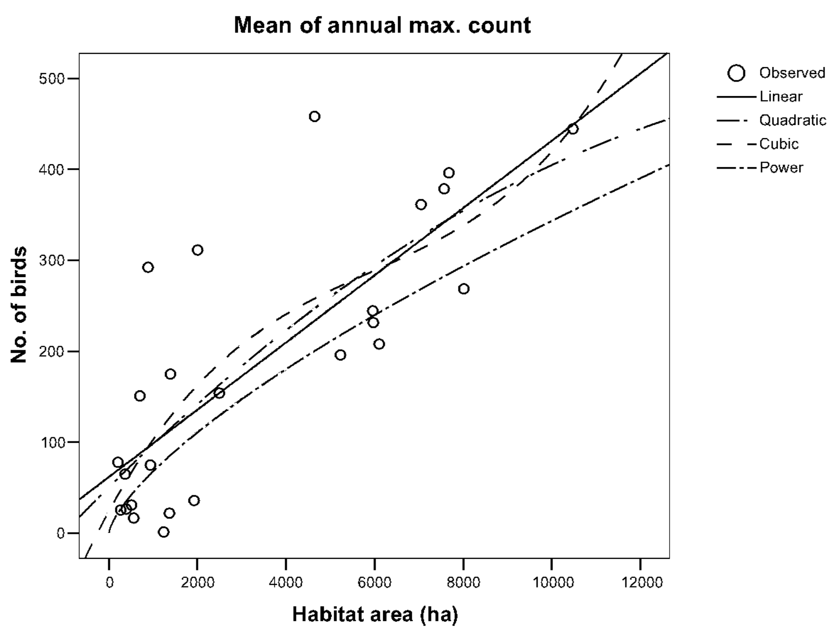


Figure 4. Plots of murrelet radar counts on areas of likely habitat for 25 watersheds on southwest Vancouver Island. The upper graph shows the annual mean count per watershed and the lower graph the mean of the annual maximum count.

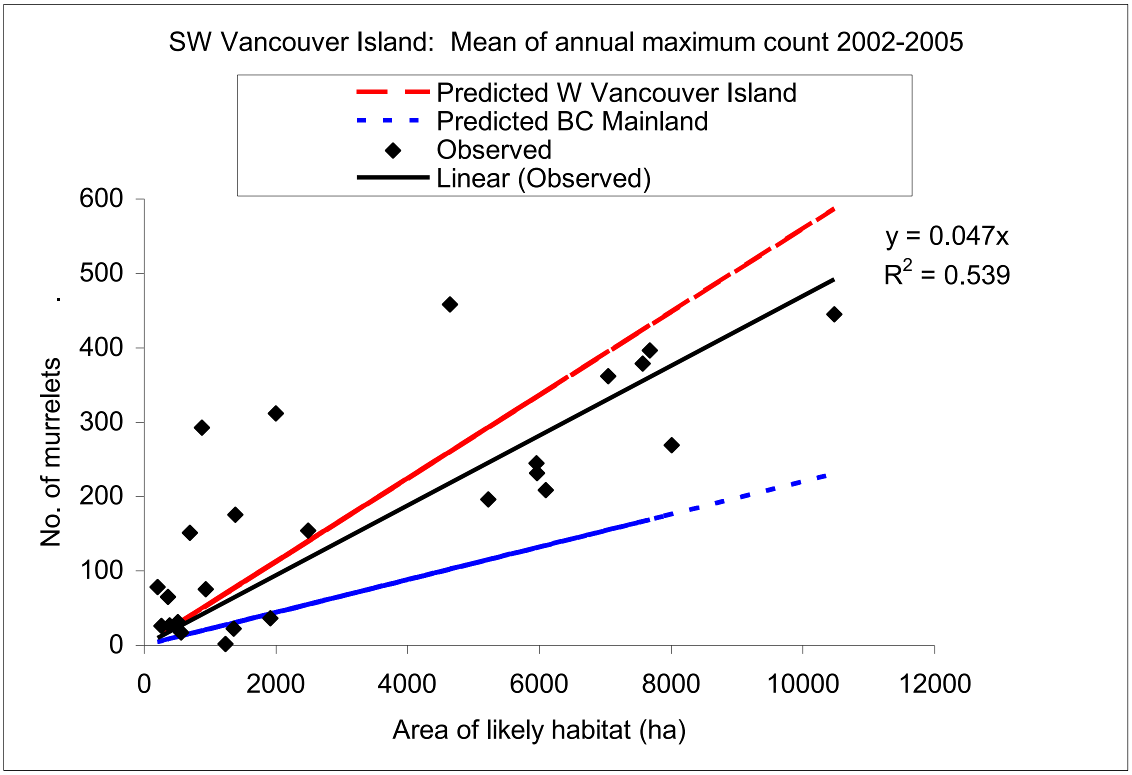


Figure 5. Radar counts of Marbled Murrelets on southwest Vancouver Island plotted against habitat area, with the regression forced through the origin. The data from our study are compared here with the regressions derived for similar counts (mean of the annual maximum count) from other studies on the west Vancouver Island (dashed red line) and the British Columbia mainland coast (dotted blue line) (Burger et al. 2004).