Research Options to Address Knowledge Gaps on Marbled Murrelet Terrestrial Habitat Requirements

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BRITISH COLUMBIA

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Alan E. Burger, F. Louise Waterhouse, and Jenna L. Cragg

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This report identifies knowledge gaps on Marbled Murrelet (*Brachyramphus marmoratus*) terrestrial habitat requirements, and research options to address those gaps and facilitate the recovery of Marbled Murrelets breeding in British Columbia, as specified by the Marbled Murrelet Recovery Strategy (Environment Canada 2014) and the British Columbia government's Implementation Plan for the species (BCMFLNRORD 2018). The report focusses on forest nesting habitat and considers marine foraging habitat only as it might apply to inland forest use and murrelet nesting behaviour. The report covers ongoing research, including how it may be expanded to address problems that have long limited reliable habitat identification and mapping. The report considers additional research needs, with particular attention given to new knowledge gaps such as future changes that are likely with climate change, and the application of new research and monitoring technologies.

The information is organized hierarchically into three levels: themes, gaps, and questions. The order of information presented follows general biological groupings and does not reflect ranked priorities for research. The format is amenable to ranking by others, such as recovery and implementation teams. The following knowledge gaps, which are the main drivers for research needs, are grouped within four general themes:

A) nesting habitat requirements (gaps 1–6),
B) habitat identification, recruitment, and supply (gaps 7–9),
C) ongoing and likely future factors affecting Marbled Murrelets (gap 10), and
D) population dynamics, demographic rates, and genetics (gaps 11–13).

Research study options are drawn from the knowledge gaps but require flexibility for development over time; hence, they are simplified to key questions, objectives, and additional considerations, if applicable. Questions once developed into studies may produce results that address multiple gaps concurrently.

Knowledge gaps are summarized under the four main themes as follows:

A) Nesting Habitat Requirements

1. Determining regional variation of nest sites and habitat – Most of the known nest sites in British Columbia are on the Sunshine Coast and southwest Vancouver Island. The paucity of nest sites from northern regions limits the development and testing of habitat algorithms. Efforts to identify nesting habitats in the north and test habitat selectivity and requirements are needed to validate habitat classification. Finding nests using telemetry involves expensive multi-year projects. Alternative methods for confirming breeding at different spatial scales could include radar, audio-visual (AV[1]), and autonomous acoustic recording unit (ARU) surveys, although these methods lack the resolution to locate actual nest trees. Future improvements in the size, attachments, and spatial resolution of satellite tracking tags (e.g., Pin-Point GPS-Argos satellite tags) should allow this technology to be used to locate nests and nest stands, at lower costs than traditional VHF radio-tracking using aircraft.

1 Initialisms and acronyms are defined in Appendix 1.

2. **Understanding the relationship between habitat quality and nesting density –** In British Columbia, Marbled Murrelet habitat management considers the ranked top three of six classes as "suitable" habitat for management (e.g., Burger and Waterhouse 2009; BCMFLNRORD 2018). Overall, there remains uncertainty about whether murrelets nest in higher densities in the highest-ranked habitats (Classes 1 and 2), although known nests have been found predominantly in higher-ranked habitats (Burger et al. 2018). While at a landscape scale there is evidence that murrelet abundance is positively affected by increased total amounts of old-growth nesting habitat (Burger 2004b), testing at this scale has not shown a relationship between abundance and classed habitat quality (Cortese 2011). Research is needed to clarify this to improve management prescriptions for Marbled Murrelet habitat because the High and Very High classes overlap the most productive forest sites yet generally comprise a smaller proportion of suitable habitat, at least as mapped using low-resolution low-level aerial surveys (LLAS) or air photo interpretation (API) (e.g., Waterhouse et al. 2011). Population modelling by Steventon et al. (2003) indicated that the probability of murrelet population persistence was sensitive to both the amount of habitat retained and nest density or habitat quality.

3. **Understanding the effect of landscape condition on site-level occupancy, including the use of small habitat patches –** The effects of patch size on the likelihood of attracting nesting murrelets and on their breeding success within small patches is unknown but is important for spatial mapping of habitat to meet management targets. Edge effects from predators and deleterious micro-habitats are exacerbated in small patches, but this has not been reliably quantified to be taken into account in forest management and the establishment of protected nesting habitat.

4. **Quantifying and managing edge effects and predation –** Most murrelet nests located to date have been close to edges (either natural or human-made), and there is convincing evidence that predation and deleterious microhabitats exist at some edge types, notably when old-growth habitat borders new clearcuts, roads, or regenerating forest that is 20–40 years old (i.e., hard edges). Information is needed on predation risk in British Columbia and how predators respond to forest fragmentation and human presence at multiple temporal and spatial scales from individual patches to the landscape level.

5. **Linking marine and terrestrial factors affecting Marbled Murrelets –** Several studies have demonstrated the close association between concentrations of murrelets at sea and areas of suitable habitat inland at varying spatial scales (e.g., Hazlitt et al. 2010). These studies highlight knowledge limitations on the importance of the effects of adjacent marine conditions, including marine productivity, on nesting success. Furthermore, effects of climate change on murrelets are likely to be stronger at sea than inland. Range-wide comparisons of inland habitat use and behaviour with marine distributions and marine foraging conditions over time are needed to investigate the importance of adjacency between inland and marine habitats, and future effects of climate change. Such studies might be possible once the Environment and Climate Change Canada marine distribution database has been completed and those data are combined with historical inland data collected from radar and AV, and available landscape-level habitat data. Databases with repeated at-sea survey data that could support finer-scale comparisons may be available for southwestern Vancouver

Island (Parks Canada surveys) and the Salish Sea (proposed surveys by Environment and Climate Change Canada). Telemetry studies that track murrelets at sea and inland would contribute to understanding these habitat links, particularly if they are linked directly with simultaneous prey surveys. The additional research on prey populations (e.g., surveys of intertidal spawning locations) would contribute to understanding murrelet at-sea distribution relative to inland nesting habitat.

6. Understanding the importance of site re-use for spatial habitat management – The continued use of nest trees and nesting stands is important for long-term spatial management of this habitat and for maintaining local populations. Setting aside forested areas (e.g., Wildlife Habitat Areas [WHAs]) often has an economic impact, and if murrelets were no longer using such areas (either because of habitat change or population shift), it would serve no conservation benefit for murrelets. Despite the importance of site fidelity, surprisingly little research has focussed explicitly on this topic (reviewed by Plissner et al. 2015[2]), although the Oregon Marbled Murrelet Project team at Oregon State University is addressing this as part of their research.

B) Habitat Identification, Recruitment, and Supply

7. Reliable identification of nesting habitat (improving habitat predictors) – None of the methods currently used to identify and map Marbled Murrelet nesting habitat in British Columbia are highly reliable at a range of spatial scales; instead, maps are used mainly to provide strategic guidance. A common problem is the inability of methods, such as using air photos or broad-scale low-resolution LLAS, to identify the presence and relative abundance of potential nesting platforms on trees. Also, some murrelets nest in suitable trees that occur singly or as part of small suitable patches, and some nest on structures other than trees, such as cliff ledges. No matter how accurately defined, these sites cannot be reliably identified with current tools, and they often occur within areas mapped as unsuitable for habitat. Conversely, habitat initially mapped as suitable (Class 1–3) using polygon-based LLAS or API ranking may over-rank these polygons after partial harvesting has occurred if the portion of the stand harvested contained the largest candidate nest trees.

8. Testing new technologies to improve habitat identification, classification, and mapping – This is ongoing. Once methods are established to improve the identification of nesting sites or potential nesting structures, efforts to improve habitat mapping of habitat quality class and its spatial location can be undertaken. Increasingly, reliable fine-scale mapping is needed to support implementation planning at the stand level; without accurate mapping, there will be uncertainty around meeting recovery population targets through retention of breeding habitat. Emerging technologies to detect murrelets and identify and map their nesting habitat that require ongoing testing include the following:

- Improved satellite tracking, such as using new Pin-Point GPS-Argos satellite tags, which are 3.5 g and have a spatial resolution of approximately 10 m, could potentially be used to locate nests. This would avoid the high costs of

2 Plissner, J.H., B.A. Cooper, R.H. Day, P.M. Sanzenbacher, A.E. Burger, and M.G. Raphael. 2015. A review of Marbled Murrelet research related to nesting habitat use and nest success. Oreg. Dep. For., Salem, Oreg. Unpubl. rep. https://www.oregon.gov/ODF/Documents/WorkingForests/ReviewofMAMUResearchRelatedToNestingHabitatUseandNestSuccess.pdf.

aerial tracking (i.e., using helicopters), which regular VHF radio telemetry requires. Such tags have been used on birds that are of similar size to murrelets. However, murrelets, like other wing-propelled diving birds, are highly sensitive to externally attached devices; past studies have revealed changes in behaviour, reduced breeding propensity and success, susceptibility to predation, and even mortality with the use of radio- or satellite-tags. Further testing is needed before such tags can be used for nest location and habitat studies, and to ensure the reliability of the satellite plus Pin-Point technology.

- Autonomous acoustic recording units have been used in several Marbled Murrelet studies to determine presence, relative abundance, seasonal and diurnal periods of activity, and habitat affinities. Sampling with ARUs is currently best applied to stand-level habitat analysis, but research is ongoing to explore applications at other spatial scales, such as using acoustic arrays to sample larger polygons. Testing the reliability of ARUs to detect murrelets and sample nesting habitat use and habitat selection, in conjunction with radar surveys to determine actual numbers of murrelets, is ongoing.
- Light detection and ranging (LiDAR) involves the use of lasers to generate three-dimensional computer images of complex structures. LiDAR has been tested in two pilot studies to assess its value in identifying and classifying forest habitat for murrelets. It currently cannot sample tree branch size (a direct measure of nest platform potential), but it can measure canopy structure and tree size, from which nesting platform potential is inferred. Possibly the most useful application of LiDAR is its potential to identify small patches or single trees that are large enough to provide suitable nest sites within otherwise unsuitable larger forested stands or non-forested areas. Testing nest habitat selection using LiDAR mapping has yet to be undertaken in British Columbia. It is not known if LiDAR is more reliable or cost-effective than API or LLAS for this purpose. And LLAS may still be required to confirm platform availability.
- Unmanned aerial vehicles (UAVs or drones) are being tested in Oregon by the Oregon Marbled Murrelet Project team to locate murrelet nests, but they remain unproven for this task. Unmanned aerial vehicles might also be used to assess canopy suitability and platform availability by modifying the methods currently used for low-level aerial surveys with helicopters. One pilot study that tested UAVs for canopy assessment had mixed success, but drones are now used for similar forestry applications, and with rapidly developing technology, they might have a useful application in murrelet habitat studies.

9. Understanding recruitment of nesting habitat from regenerating forest – Recruitment of suitable nesting habitat through the maturation of older regenerating forest is part of the long-term strategy to increase and maintain nesting habitat in areas that are depleted below the retention amounts recommended by the Canadian Marbled Murrelet Recovery Team, especially in the East Vancouver Island Conservation Region (BCMFLNRORD 2018). Three studies in British Columbia have modelled landscape recruitment of habitat as forests age (Tomlins and Gray 2006[3]; Long et al. 2011; Sutherland, G.D. et al. 2016), and

3 Tomlins, M. and M. Gray. 2006. Marbled Murrelet nesting habitat trends for the Sunshine Coast Forest District. B.C. Min. Agric. Lands, Integrated Land Manag. Bureau, Victoria, B.C. Unpubl. rep.

two studies have analyzed the stand-level development of potential nest platforms as trees age and increase in size (Burger et al. 2010; Sutherland et al. 2016b). This information is valuable for supply modelling of nesting habitat (e.g., Steventon et al. 2006). The available data show considerable variability in potential for habitat recruitment across regions, Biogeoclimatic Ecosystem Classification (BEC) zones, elevation, topography, and tree species, which indicates a need for broader sampling and further analyses to more reliably predict and manage habitat supply over time. If the collection of metrics that describe murrelet nest platform potential is integrated into forest inventory, such as permanent sample plots, these data would become available for investigating these questions.

C) Ongoing and Likely Future Factors Affecting Marbled Murrelets

10. Climate change influences on murrelet habitat availability and distribution – There have been very few studies of factors that affect canopy epiphytes (primarily bryophytes), which provide the bulk of murrelet nests (van Rooyen et al. 2011). Such studies are needed, especially to test the effects of edge type and forest fragmentation, combined with the likely effects of warmer and windier summers due to climate change, on forest development and growth projections. Conditions that favour coastal BEC zones and the trees most often used by nesting murrelets are expected to change with changing climates. However, widespread mortality of favoured trees is not expected by 2080, and changing climate (warmer summers and increased winds) is likely to have stronger negative effects on the viability of canopy epiphytes (mostly mosses) than on the trees themselves. These canopy effects will be strongest at forest edges and in fragmented habitat. Research and baseline data are needed to understand likely changes in epiphytic mossy platforms across the murrelet's British Columbia range, but especially in the moister Coastal Western Hemlock (CWH) forests of southern British Columbia, such as the CWHvm (very wet maritime subzone) used by many nesting murrelets, where future conditions seem likely to favour drier ecosystems (e.g., Coastal Douglas-fir [CDF] or CWHxm [very dry maritime subzone] biomes).

D) Population Dynamics, Demographic Rates, and Genetics

11. Population demography and vital rates of Marbled Murrelets in British Columbia – Data are limited to one geographic region (Desolation Sound) and were collected from 1991 to 2000 (Lougheed 2000; Cam et al. 2003). Throughout the rest of the province, no information has been collected to estimate rates of survival, fecundity and breeding propensity, immigration/emigration, or juvenile dispersal, and how these factors could interact with other pressures on the population to influence overall population trends. For example, it is unclear whether observed population declines in a given conservation region are partially driven by movements of adults in response to poor marine conditions or result from reduced survival and breeding effort and success (and truly negative population growth rates) in response to terrestrial habitat conditions. Related issues affecting population dynamics that are poorly known for British Columbia murrelets include migration (between British Columbia and adjacent U.S. states, and among the conservation regions within British Columbia) and philopatry.

12. Philopatry – Current understanding of philopatry in murrelets remains limited. Movement of murrelets between watersheds or subregions or across regions in response to habitat conditions, either marine or terrestrial, is poorly understood but is suspected to contribute to annual regional changes in abundance. However, it is unclear whether individuals move in response to poor marine conditions then return to their natal watersheds when conditions improve. Evidence of variable site fidelity at the nest site and nest tree has been documented but at the population level; it is not known how these patterns affect abundance and distribution at various spatial scales. Potential population source–sink dynamics have not been explored in British Columbia. Watersheds with large areas of remaining suitable habitat adjacent to productive marine habitat may act as source populations from which individuals disperse to neighbouring areas. These dynamics could mask underlying effects of habitat fragmentation, predation, or poor marine conditions in population sinks. Areas identified as source populations may also be more important to prioritize for habitat protection.

13. Population genetics and genetic divergence – There is very little information about these topics from British Columbia. Friesen et al. (2005) found that British Columbia murrelets were lumped with mainland Alaska murrelets into one population unit based on neutral genetic variation from mitochondrial DNA. More recent analyses have shown that major histocompatibility complex class II B genes can be used to improve the delineation of murrelet conservation units by identifying populations that harbour local adaptations (Vasquez-Carrillo et al. 2014), but these analyses have not been performed on samples from British Columbia. Understanding genetic adaptations and structures would inform the importance of maintaining breeding habitat coast-wide and at various scales within; that is, regional to local.

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APPENDIX

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1 INTRODUCTION AND BACKGROUND

This report investigates ongoing and future research needs to facilitate the management of forest nesting habitat used by the Marbled Murrelet (*Brachyramphus marmoratus*) in British Columbia. This is not an exhaustive review of the biology of the species, its nesting requirements, or management options. It is intended as a first step in renewed discussion on knowledge gaps and research needed to address those gaps and inform the Marbled Murrelet Recovery Strategy (Environment Canada 2014; Manning et al. 2019) and the British Columbia government's implementation plan for the species (BCMFLNRORD 2018). Particular attention has been paid to considering how the predicted effects of climate change on forest nesting habitat may influence long-term management, and to the potential application of new technologies for studying the Marbled Murrelet and its terrestrial habitat.

The report focusses on forest nesting habitat but recognizes that murrelets' use of this habitat is also strongly influenced by the availability of suitable foraging habitat in adjacent coastal seas. The strongest effects of climate change are likely to be experienced in this marine habitat, but reviewing those changes is beyond the scope of this report. There are, however, some suggested research options that combine research or monitoring in both marine and forest habitats. Predation is a major cause of Marbled Murrelet nest failure. This review considers only knowledge gaps that require research related to terrestrial habitat modification (e.g., edge effects) (Malt and Lank 2007, 2009; Raphael et al. 2018).

Apart from a few nests found on mossy cliff ledges and large deciduous trees, most Marbled Murrelets that nest in British Columbia typically use canopy boughs of large coniferous trees in coastal forests, generally within 30 km of the ocean; this habitat is the primary focus for maintaining murrelet populations across the species' range in British Columbia (Burger 2002; CMMRT 2003; COSEWIC 2012; Environment Canada 2014). Nearly all the forest nests found in British Columbia were on mossy pads, and the development of mossy pads on canopy limbs is considered to be a key feature of required habitat (Burger et al. 2010). Scoring the availability of potential nest platforms (defined as mossy pads, limbs, or deformities > 15 cm in diameter) is one of the key elements of habitat classification (RIC 2001; Burger, Smart, et al. 2004). The factors that affect the availability of mossy platforms and the methods for identifying that availability are therefore one of the key issues addressed in this review.

2 ONGOING KNOWLEDGE GAPS BY THEME: QUESTIONS AND PROBLEMS

This section deals with issues that are known to need attention in dealing with Marbled Murrelet nesting habitat in British Columbia, and it identifies where there are still outstanding questions and uncertainties. This section briefly reviews the information on each issue, provides links to relevant literature, and summarizes the main needs for future improvement.

2.1 Nesting Habitat Requirements

2.1.1 Determining regional variation in nest sites and habitat Several studies have shown regional variations in the key parameters (e.g., size and species of trees, and effects of aspect and elevation) used for estimating forest habitat suitability across British Columbia (e.g., Nelson 1997; Burger 2002; Waterhouse et al. 2009; Burger et al. 2010), but known nest sites, which provide the strongest data for testing habitat preferences, are concentrated in a few areas (predominantly the Sunshine Coast, Clayoquot Sound and a few other areas on southwest Vancouver Island, and Haida Gwaii). Two regions that support large populations of breeding murrelets (based on at-sea and radar surveys)—the Northern and Central Mainland Coast Conservation Regions—have very few known nest sites (e.g., Mussel Inlet on the southern edge of the Central Mainland Coast Conservation region), and very few audio-visual surveys or habitat plots have been done in these regions (see Burger et al. 2010). Testing regional variations in habitat use and refining habitat mapping models for these areas (e.g., the B.C. Model) (Mather et al. 2010) are therefore greatly limited. Additional data for all conservation regions would improve habitat mapping and implementation.

2.1.2 Understanding the relationship between habitat quality and nesting density Most murrelet nests in British Columbia have been found in forest habitat that is predicted to be suitable (B.C. Model) or of higher quality (based on air photo interpretation [API[4]] and low-level aerial survey [LLAS] methods), although the reliability of the methods used varies considerably (Burger and Waterhouse 2009; Burger et al. 2018). In general, the relationship between nest occurrence and habitat quality ranking fits a modified threshold model (few nests in habitat ranked Very Low or Low, intermediate numbers in Moderate habitat, and similar high numbers in both High and Very High habitat), not a linear or neutral relationship (Burger and Waterhouse 2009; Burger et al. 2018). Nesting density (nests per hectare of habitat) might follow a similar modified threshold pattern, but this has not been confirmed.

Strong correlations between the area of suitable forest habitat and the number of Marbled Murrelets that likely breed have been demonstrated at the watershed/landscape level by radar studies (Burger 2001; Burger, Chatwin, et al. 2004; Cooper et al. 2006; Cortese 2011), and at the regional level by at-sea census data (Raphael et al. 2015). Beyond measures of habitat suitability, the effects of habitat quality, as classified by current modelling or API or LLAS methods, remain uncertain. Cortese (2011) examined factors that affected radar counts of murrelets in three regions (Central Coast, South Coast, and southwest Vancouver Island). As expected, murrelet numbers were most closely related to the area of old-growth forest in all regions, but additional variables that improved the predictive models varied among the regions. Density of hard and soft landscape edges was an important variable in all regions, and the matrix of suitable habitat (fragmentation) was important in two of the three regions. Murrelet numbers were positively associated with edges on the South and Central Coast but were negatively associated with them on southwest Vancouver Island (a likely effect of habitat remaining in highly fragmented watersheds on the South Coast, and in habitat with many natural edges, such as avalanche chutes, in the steeper Central Coast watersheds [Cortese 2011]). Overall, though, Cortese's (2011) models explained only 11–35% of the variability in murrelet numbers in the three regions. Cortese's (2011) study highlights the difficulties of quantifying the effects of

4 Initialisms and acronyms are defined in Appendix 1.

habitat quality on nesting density. Other factors not included in those models, such as marine conditions and commuting distances, were likely to influence murrelet numbers.

Ronconi (2008), Raphael et al. (2015), and Lorenz et al. (2016) showed that murrelet numbers at sea were strongly related to the area and proximity of suitable nesting habitat. The converse is also true — murrelet density inland is affected by nearby marine foraging opportunities (Meyer et al. 2002; Hazlitt et al. 2010). Burger, Chatwin, et al. (2004) showed that commuting distance was an important secondary factor, after habitat area, in explaining radar counts in watersheds on British Columbia's North and Central Coast, where long, unproductive fjords separate nesting and foraging habitats. This suggests that in many areas of the Central and North Coast regions, fjord topography and commuting distance, in addition to habitat area, habitat quality, and marine foraging opportunities, affect the use of suitable inland habitat. The effects of variable marine conditions on the annual number of murrelets nesting in any area are also important. Verification of nesting using short-term monitoring in any area — a Wildlife Habitat Area (WHA), for example — based on radar, audio-visual (AV) surveys, or automated recording units (ARUs) could be affected if few murrelets initiate nesting or nest successfully during periods of low prey availability. There are indications that this happens on southwest Vancouver Island (Burger 2000; Ronconi and Burger 2008). The Oregon Marbled Murrelet Project team at Oregon State University is currently investigating how nesting habitat quality, area, and proximity to the ocean affect the settlement and persistence of murrelets during fluctuating ocean conditions that affect prey availability (M. Betts, Oregon State University, pers. comm.). Large-scale movements of murrelets — for example, from one conservation region to another — might also occur during periods of poor marine conditions, such as in El Niño years. Temporary immigration of murrelets linked to oceanic changes has been reported in California (Peery, Becker, et al. 2006; Peery et al. 2009).

Overall, there remains uncertainty about whether murrelets nest in higher densities in habitats ranked High or Very High (Classes 1 and 2 in API and LLAS methods) compared to Moderate (Class 3), as reviewed by Burger and Waterhouse (2009). There is a need for research to clarify this to improve management prescriptions for Marbled Murrelet habitat. The management approach has been to consider these top three ranks as "suitable" habitat (e.g., BCMFLNRORD 2018; Manning et al. 2019), but efforts are generally made, where optional, to include Classes 1 or 2 in habitat that is specifically being set aside as Marbled Murrelet nesting habitat; for example, in WHAs (BCMOE 2004). At larger spatial scales (e.g., landscape unit planning), there is a risk that the intermediate Class 3 might be over-represented in habitat that is set aside for murrelets to meet conservation region targets (because Class 1 and Class 2 often overlap with the most productive forest), at least as mapped using low-resolution LLAS or API (e.g., Waterhouse et al. 2011), and the better Class 1 and 2 habitats might then be lost. Management decisions regarding retention of habitat by quality class could be made with more certainty if research clarified and quantified the relationship between nesting density and habitat quality.

2.1.3 Understanding the effect of landscape condition on site-level occupancy, including the use of small habitat patches A related issue is to understand the effects of patch size, relative to the surrounding land matrix, on the likelihood of attracting and retaining nesting murrelets, and on their breeding success. This issue has long been debated in British Columbia (e.g., Burger 2002; CMMRT 2003) and remains unresolved. Edge effects, known to affect nesting murrelets due to increased predation risk and adverse microclimates (reviewed by Raphael et al. 2018) are exacerbated as patch size becomes smaller and interior forest habitat is reduced (see the geometric models in Burger 2002). There is some evidence that murrelet abundance declines in fragmented landscapes (e.g., Meyer and Miller 2002; Meyer et al. 2002; Cortese 2011). Meyer et al. (2002) indicated that lower likelihood of occupancy of habitat in isolated patches was potentially due to reduced conspecific attraction. Research on landscape fragmentation in British Columbia has had mixed results (Zharikov et al. 2006, 2007; Burger and Page 2007). The problematic outcome of this lack of consensus is that at a landscape scale, habitat targets may be more easily achieved by using a greater number of smaller patches compared to fewer larger patches in an operational landscape. Our understanding of minimum patch size thresholds and related landscape condition due to fragmentation effects needs further quantification in order to be taken into account when establishing protected spatialized nesting habitat and tracking habitat management targets. New research that is testing patch size and landscape condition in relation to murrelet occupancy is currently under way.[5]

2.1.4 Quantifying and managing edge effects and predation Across the species' range, about 75% of murrelet nests have been located close to forest edges, either natural or human-made (McShane et al. 2004[6]). Nests at hard edges (old-growth forest bordering clearcuts, roads, or regenerating forest < 40 years old) are, however, more susceptible to predation, adverse microclimates, and exposure to wind and sun (reviewed by van Rooyen et al. 2011; Burger 2016; Raphael et al. 2018). Risk modelling suggested that edge effects were clearly secondary (but not trivial) to amount and quality of nesting habitat in determining population persistence in British Columbia (Steventon et al. 2006). When establishing WHAs for murrelets, the Identified Wildlife Management Strategy guidelines recommend minimizing edge effects by avoiding creation of hard edge, small old-growth patches, and forest fragmentation (BCMOE 2004). Research and monitoring of populations of the primary edge predators (ravens, crows, and jays) in these sensitive areas would also give a better understanding of the risks to nesting murrelets, especially if studies were done across a wide range of forest fragmentation and edge types.

Studies on the effects of nest predators have been an important focus of murrelet recovery in the United States (reviewed by McShane et al. 2004; Raphael et al. 2018), especially in California, where murrelet habitat is highly restricted and often in parks, which in turn are frequented by many corvids (Peery and Henry 2010). Relatively few studies have analyzed predator distributions or behaviour relative to forest fragmentation and edges in British Columbia, but they have included analyses of relative predator abundance associated with forest fragmentation on southwest Vancouver Island (Rodway

5 Contact F.L. Waterhouse (louise.waterhouse@gov.bc.ca) or J. Cragg (jenna.cragg@gov.bc.ca), FLNRORD.

6 McShane, C., T. Hamer, H. Carter, G. Swartzman, V. Friesen, D. Ainley, R. Tressler, K. Nelson, A. Burger, L. Spear, T. Monagen, R. Martin, L. Henkel, K. Prindle, C. Strong, and J. Keany. 2004. Evaluation report for the 5-year status review of the Marbled Murrelet in Washington, Oregon, and California. U.S. Fish Wildl. Serv., Reg. 1. Portland Oreg. Unpubl. rep. http://www.fws.gov/oregonfwo/species/data/marbledmurrelet/documents/2004fiveyearreviewreport.pdf.

and Regehr 2002; Burger, Masselink, et al. 2004), documentation of the spatial and behavioural responses of Steller's Jays (*Cyanocitta stelleri*) to forest fragmentation on southwest Vancouver Island (Masselink 2001), and studies at artificial nests to document survival of nest contents relative to edge effects and visitation by predators (Malt and Lank 2007, 2009). With populations of corvids and some raptor predators increasing in parts of the murrelet's range in British Columbia (Piatt et al. 2007), additional studies of predator distributions and behaviour in British Columbia could help in assessing predation risk and optimal layout of protected habitats. Once again, this research appears to be most valuable in the regions where habitat is most reduced and fragmented and where human influences that attract corvid predators are most likely; that is, the East Vancouver Island and Southern Mainland Coast Conservation Regions. The research being conducted on patch use has incorporated the testing of indices of predator activity at the same sites.[7]

2.1.5 Linking marine and terrestrial factors affecting Marbled Murrelets

Nesting Marbled Murrelets require access to both adequate foraging habitat at sea and nesting habitat inland. Following the discussion presented in Section 2.1.3, several studies have demonstrated the close association between concentrations of murrelets at sea and areas of suitable habitat inland at varying spatial scales (e.g., Burger, Chatwin, et al. 2004; Ronconi 2008; Raphael et al. 2015; Lorenz et al. 2016). Hazlitt et al. (2010) recommended that adjacent marine conditions be considered in planning inland nesting reserves for the murrelet. Mapping of the marine distributions of Marbled Murrelets is in progress,[8] but much of the British Columbia coast has not been surveyed for murrelets. In addition, measures of prey availability and mapping of key marine habitat features are expected to be included in a partial identification of marine Critical Habitat mapping needed to satisfy the recovery strategy (Environment Canada 2014). These marine parameters could be used to investigate the role that marine habitat and food have in the distribution of nesting murrelets and their breeding success in British Columbia. Future telemetry studies, perhaps using tags similar to the Pin-Point GPS-Argos satellite tags (see Section 2.2.2) could provide valuable information on the concurrent use of marine foraging and terrestrial nesting habitats by individual murrelets.

Long-term at-sea monitoring of Marbled Murrelets along coastal stretches is being conducted at only two locations: Laskeek Bay in Haida Gwaii, and off Pacific Rim National Park Reserve, southwest Vancouver Island (COSEWIC 2012). In the latter area, Ronconi (2008) showed the strong relationship between concentrations of murrelets at sea and nearby areas of suitable nesting habitat. Cragg (2013) showed that radar counts of murrelets on Kodiak Island, Alaska were most closely correlated with at-sea numbers within a spatial radius of 5 km of the radar station. Environment and Climate Change Canada plans to conduct additional surveys to cover parts of the Salish Sea, which could provide information that can be compared with nesting habitat on southern Vancouver Island and the southern Mainland Coast.[9]

7 Contact F. L. Waterhouse (louise.waterhouse@gov.bc.ca) or J. Cragg (jenna.cragg@gov.bc.ca), FLNRORD.

8 D. Bertram, Environment and Climate Change Canada, Institute of Ocean Sciences, Sidney, B.C., pers. comm.

9 K. Woo, Environment and Climate Change Canada, Delta, B.C., pers. comm.

The data from existing localized marine surveys, and additional planned marine surveys, could be used for future studies of spatial and temporal changes in murrelet numbers (radar) and inland activity (AV and ARU surveys). This would give a better understanding of the factors that are limiting murrelet populations and determining their breeding success. Ronconi and Burger (2008) showed how adverse marine conditions off southwest Vancouver Island reduced the recruitment of fledged juveniles, and Burger (2000) showed that AV detections in that area were affected by periodic warm-water events in the nearshore waters.

Radar has become the standard method of monitoring watershed-level populations at selected sites across six of the Marbled Murrelet conservation regions (Bertram et al. 2015), and this method has sufficient statistical power to detect likely population changes (Arcese et al. 2005[10]). In addition, radar is a powerful tool for showing the effects of habitat loss within watersheds (Burger 2001; Burger, Chatwin, et al. 2004). Radar can also be applied in conjunction with other tools (AV and ARU surveys) that identify stand-level presence or occupancy, measures of seasonal activity (Cragg et al. 2015, 2016). Radar could be used to track population changes in studies that investigate habitat fragmentation, habitat recruitment, climate change effects, and links between marine and inland factors.

The inclusion of marine data would help in the interpretation of current murrelet studies (e.g., Capilano Watershed and Capital Regional District); this could include readily available data such as sea temperatures and productivity (indicated by chlorophyll), and ideally, at-sea surveys of murrelet abundance and distribution. Such data could help in understanding why murrelet use of suitable habitat might change despite few changes in forest conditions. Management of marine habitat is generally outside of provincial jurisdiction, with the exception of intertidal spawning habitat for important murrelet prey species (Pacific sand lance [*Ammodytes hexapterus*], surf smelt [*Hypomesus pretiotsus*], and Pacific herring [*Clupea pallasi*]). Mapping of the spawning sites of these important prey fish would greatly improve the reliability of models that predict the distribution of murrelets across British Columbia (Yen et al. 2004). Haynes et al. (2007) and Haynes et al. (2008) did important work on these topics on southwest Vancouver Island.

2.1.6 Understanding the importance of site re-use for spatial habitat management Understanding the fidelity of nesting Marbled Murrelets to forest stands is important for maintaining higher-quality, productive nesting habitats for long-term management of this habitat and for maintaining local populations. Setting aside forested areas (e.g., WHAs) often has an economic impact, and if murrelets were no longer using such areas (either because of habitat change or population shift), it would serve no conservation benefit for the species. Despite the seeming importance of this issue, surprisingly little research has focussed explicitly on it (reviewed by Plissner et al. 2015). At the fine scale, Burger et al. (2009) investigated the re-use of nest trees in successive seasons and found that in areas where suitable trees were relatively abundant (west

10 Arcese, P., A.E. Burger, C.L. Staudhamer, J.P. Gibbs, E. Selak, G.D. Sutherland, J.D. Steventon, S.A. Fall, D. Bertram, I.A. Manley, S.E. Runyan, W.L. Harper, A. Harfenist, B.K. Schroeder, D.B. Lank, S.A. Cullen, J.A. Deal, D. Lindsay, and G. Jones. 2005. Monitoring designs to detect population declines and identify their cause in the Marbled Murrelet. Univ. British Columbia, Cent. Appl. Conserv. Res., Vancouver, B.C. Unpubl. rep.

Vancouver Island), nest trees were seldom re-used within 4–6 years, but in areas where suitable trees were sparse (southern Mainland Coast and east Vancouver Island), re-use was much higher. In all those sites, nest success and site fidelity of the same individuals relative to re-use was unknown. Regardless, while re-use of a nest tree within a stand helps confirm the importance of the stand, failure to detect re-use of the nest tree does not explain whether or not other trees within the same stand are subsequently used by the same or new individuals.

In the Bunster Range (Southern Mainland Coast Conservation Region), where up to 80% of original habitat has been removed (Zharikov et al. 2006), Manley (1999) found that 52% of 36 nest sites were associated with another nest tree within 100 m, although not all nests were active at the same time. Manley (1999) suggested that nest clusters might represent multiple nesting attempts in the same stand by a breeding pair and therefore indicate fidelity to a forest patch rather than a specific tree. When investigating re-nesting at the stand level, Plissner et al. (2015) found data only for individual tree nests, and since not all the trees in the stands were sampled, the authors could not estimate average re-nesting in stands. At the stand level, fidelity of use (i.e., occupancy or known nests) was found in ≥ 40 of the ≥ 57 stands studied (including all 15 stands in British Columbia), but only six of those instances involved re-use by tagged birds, and the rest represented re-use by unknown individuals. Site fidelity seems higher at larger spatial scales (Plissner et al. 2015). At the watershed scale, there is consistent evidence of fidelity (evidence of consistent use in all 37 watersheds from 23 studies, including > 15 watersheds in British Columbia). With the exception of two tagged birds, this represents evidence of re-use of watersheds by unknown (same or different) individuals.

Determining site fidelity by individuals requires radio-tagging, and is an expensive undertaking. Determining consistent use of stands by unknown individuals is considerably simpler but of equal importance in maintaining habitat that is actually used by murrelets. The primary tools, other than telemetry, would be radar surveys, deployment of ARUs, and ideally, AV surveys (allowing measures of occupancy rather than simply detections). The Pacific Seabird Group monitoring protocols (Evans Mack et al. 2003) and British Columbia equivalent (RIC 2001) provide guidance on the AV survey effort needed to prove site occupancy.

2.2 Habitat Identification, Recruitment, and Supply

2.2.1 Reliable identification of nesting habitat (improving habitat predictors)

As shown in a recent review (Burger et al. 2018), none of the methods currently used to identify and map Marbled Murrelet nesting habitat in British Columbia are highly reliable. A common problem is the inability of methods to identify the presence and relative abundance of potential nesting platforms. Of the methods now commonly used, only ground surveys (usually in vegetation plots) (RIC 2001) and LLAS using a helicopter (Burger, Smart, et al. 2004) provide estimates of platform availability. Even intensive, plot-centred LLAS failed to correctly classify 15% of actual nest sites as suitable habitat, even though nearly all were in trees (Burger et al. 2018). Improving the reliability of habitat identification and mapping, especially for large tracts of land (watersheds and landscape units) and for finer-scale resolution to implement Land Use Orders, is therefore an ongoing and important need for management.

Related to this problem is the issue of how to deal with nests that occur outside "suitable" habitat, no matter how accurately defined (Burger et al. 2018). This is not unique to Marbled Murrelets; indeed, almost all wildlife species will at times use habitat that humans do not recognize as suitable, or that is atypical for the species. Being able to recognize and quantify the number of nests within larger polygons of habitat that is currently classed as "unsuitable" is a key to determining the application of the Marbled Murrelet Recovery Strategy's goal of maintaining 70% of the forest habitat that was available in 2002 (Environment Canada 2014; BCMFLNRORD 2018). Generally, there are two ways that nest sites are missed. The first is that the nest structure is something other than a suitable platform tree — for example, a cliff ledge. Development of separate algorithms to identify areas that are likely to support these structures would be required, but currently there are too few such nests for analysis. The second is that the potential or actual nest occurs in a single suitable tree or in a small patch (e.g., < 1 ha) within a matrix of non-forest or forest with lower suitability (e.g., Class 4 or 5). Mapping scale and resolution, for practical purposes, can be too coarse to identify these locations; therefore, alternative tools may be needed to identify the potential availability of these sites.

A related issue is the difficulty of identifying small clusters of suitable trees within otherwise unsuitable polygons. Burger et al. (2018) identified this as a key issue in the overall management of Marbled Murrelet habitat in British Columbia, given that polygon-based LLAS correctly classified only 47% of nest sites in Desolation Sound as suitable habitat, and even patch-level intensive LLAS classified only 85% of known nest sites as suitable. Identifying small patches of suitable habitat within larger polygons of averaged unsuitable habitat is valuable for at least two reasons. At the strategic level, this would allow these smaller patches of habitat to be included in the overall tally of suitable habitat, which provides the denominator for calculating critical habitat (70% of suitable habitat area [hectares] across all regions in British Columbia [Environment Canada 2014]). Secondly, as Clyde (2017) pointed out, if there was some agreement on minimum patch size for inclusion, then these cryptic patches of habitat might be included in protected areas, such as WHAs. Inclusion of larger polygons of Class 4 or 5 habitat is not economically or biologically viable for Marbled Murrelet management (Burger et al. 2018), but smaller patches of suitable habitat within these lower-class forests might be considered.

Approaches to addressing these limitations include conducting additional sampling to improve classification models, and developing new technologies to identify habitat and develop new classification models, such as LiDAR-based suitability mapping (see Section 2.2.2).

Across the murrelet's range in British Columbia there is considerable variation in tree species dominance and topographic and landscape influences (e.g., long fjords on the Central and North Coasts). Increased sampling to identify suitable nesting habitat — for example, vegetation plots or LiDAR imaging linked with AV or ARU surveys — in poorly sampled areas of British Columbia would allow the development of regional habitat suitability models. Regional models are likely to be more reliable than the coast-wide B.C. Model, which is known to have limited success in reliably predicting nesting habitat that is actually used (Burger et al. 2018). As an example, the regional model for Clayoquot Sound developed by Bahn and Newsom (2002a, b), which used fine-scale Vegetation Resource Inventory (VRI) data, appears to be a more reliable predictor than the general B.C. Model in most areas where such fine-scale VRI data are lacking.

2.2.2 Testing new technologies to improve habitat identification, classification, and mapping

Satellite and GPS tracking Regular VHF radio-telemetry tracking has been a key tool in locating Marbled Murrelet nests and hence providing information on nesting habitat use at a range of spatial scales (e.g., Zharikov, Lank, et al. 2006; Zharikov, Lank, and Cooke 2007; Silvergieter and Lank 2011; Barbaree et al. 2014), but it requires the expensive use of helicopters or fixed-wing aircraft. A few pilot studies have used satellite platform terminal transmitters (PTTs) to track Marbled Murrelets. In British Columbia, Bertram et al. (2016) used satellite tags to map coarse space use patterns in Douglas Channel to assess their overlap with shipping routes. Research in Oregon led Northrup et al. (2018) to conclude that current PTT technology does not appear to be suitable for locating Marbled Murrelet nest sites (location data are too coarse) and can lead to adverse effects and mortality.

Future improvements in technology, device size, and spatial resolution should allow satellite tracking to be used for finer-scale location of nests and nest stands. Recent development of small (3.5 g) Pin-Point GPS tags has allowed for the long-term tracking of birds that are of similar size to Marbled Murrelets, such as shorebirds (Scarpignato et al. 2016) and Common Nighthawks (Ng et al. 2018). The Pin-Point GPS-Argos satellite tags collect and archive up to 30 GPS locations and transmit stored locations via the Argos satellite system at pre-specified times (Scarpignato et al. 2016). GPS tags are generally accurate to within 10 m, whereas regular Argos PTTs are accurate only in the range of 250 m to >1.5 km (Scarpignato et al. 2016). A program using Pin-Point GPS-Argos or similar devices on Marbled Murrelets would require capture effort but not the subsequent intensity of search and monitoring that is needed for standard VHF radio telemetry. Such technology might therefore be particularly valuable for locating nests in the more remote areas of the Central and Northern Coast regions.

One concern with any externally attached tracking device is that diving birds, such as murrelets, are highly susceptible to the effects of underwater drag; many studies have shown detrimental effects of such devices on penguins, alcids, and other wing-propelled divers (Wilson and McMahon 2006; Burger and Shaffer 2008). For Marbled Murrelets, these effects include breeding failure, abnormal behaviour, susceptibility to predation, and mortality (Peery, Beissinger, et al. 2006; Northrup et al. 2018). Therefore, extreme vigilance is needed to ensure that any devices attached to murrelets do not significantly affect their behaviour, breeding success, or survival. The current Pin-Point GPS-Argos satellite tags require two external antennas (one for GPS and one for the Argos satellite) (Scarpignato et al. 2016), and therefore are probably not suitable for deployment on Marbled Murrelets. Testing the reliability of the satellite/GPS tags in coastal terrain will also be important before large-scale deployments.

Autonomous recording units Autonomous recording units (ARUs), also known as autonomous acoustic sensors, are increasingly used to conduct acoustic surveys for birds (Shonfield and Bayne 2017). These devices (Song Meter brand[11]) have been used in several studies on Marbled Murrelets in forested habitat to determine their presence, relative abundance, seasonal and diurnal periods of activity, and habitat affinities (Borker et al. 2015; Cragg et al. 2015, 2016; Cragg et al. 2019).

11 Wildlife Acoustics, Inc., Maynard, Mass.

Autonomous recording units are currently being tested by the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) Cragg et al. (2019) to assess whether:

1. small reserves (e.g., < 20 ha) can be used successfully by nesting murrelets; and
2. currently protected habitat reserves (e.g., WHAs, generally > 20 ha) are maintaining their effectiveness over time as the surrounding landscape changes. A key objective of the British Columbia Forest and Range Evaluation Program is to confirm the effectiveness of habitat protections by determining that sensitive wildlife actually use the reserves set aside for them.

Additional goals of this study are to assess the efficacy of using ARUs for future inventory and monitoring purposes by comparing their results with those from radar and AV surveys. This builds on similar work done by Cragg et al. (2015, 2016) on Kodiak Island, Alaska. The simultaneous use of radar and AV surveys is a valuable method for testing the reliability of the ARUs and for assessing habitat use at varying spatial scales, as shown by Cragg et al. (2015, 2016) on Kodiak Island and by Cragg et al. (2019) in British Columbia. Additional data are being collected at the research sites to index predator activity to test for effects on murrelet occupancy.

A potential application of ARU data is in the recognition of individual murrelets recorded at specific stands. Identifying individuals in ARU recordings could provide a measure of local population density, and if repeated over multiple seasons, could provide a measure of site fidelity. Such applications of sound recordings have been used successfully to identify individuals of other avian species (e.g., Grava et al. 2008). Dechesne (1998) showed that murrelets on southwest Vancouver Island might be individually distinguished based on spectrograms of their vocalizations, but this has not been developed as a censusing or monitoring tool. With the rapid advance of recording and analytical tools for animal vocalizations, it is realistic to expect that vocal recognition could soon be applied to monitoring Marbled Murrelets, estimating localized populations, and measuring site fidelity.

LiDAR

LiDAR (light detection and ranging) involves the use of lasers to generate three-dimensional computer images of complex structures. For forest research, the returns from airborne lasers are used to generate millions of points in 3-D space that can be used to measure tree height, canopy shape and structure, and many other structural measures for large areas. LiDAR represents a powerful new tool for forest and wildlife management. Two studies have specifically investigated the use of LiDAR to identify Marbled Murrelet nesting habitat.

In the United States, Hagar et al. (2014) used LiDAR-based spatial models to compare stands in Oregon that were known to be occupied by murrelets with stands that were considered to be unoccupied, as defined by the Pacific Seabird Group protocol for audio-visual surveys (Evans Mack et al. 2003). LiDAR-based measures included cover in the upper portion of the canopy, height of the tallest trees, maximum height of the bottom of the canopy, variation in cover in the upper canopy; and distribution of vegetation across canopy height intervals. Models that included these five LiDAR-based variables were considered to be superior at discriminating occupancy compared to models that were based only on forestry-derived nearest-neighbour measures. Hagar et al. (2014) also evaluated LiDAR metrics at 11 known nest sites in Oregon. Algorithms based on LiDAR-based measures accurately discriminated nest sites relative to randomly selected sites. Extending this work, Hagar et al. (2018) tested a LiDAR-based model derived from one region in Oregon (Coos Bay area) within another region (Siuslaw National Forest) to test model transferability. They concluded that the Coos Bay model could be reasonably applied to Siuslaw forests, but the inclusion of locally derived variables improved discrimination between occupancy and probable absence. Neither the Coos Bay (AUC = 0.73) nor the locally modified model (AUC = 0.79) provided discrimination that could be considered excellent (AUC values > 0.9) but could be considered good (AUC 0.7–0.9).

Clyde (2017) generated models that included LiDAR-based metrics to compare with polygon-based LLAS in watersheds of northern Vancouver Island. A balanced random forest classification algorithm based on topographic and LiDAR-based metrics performed reasonably well in predicting the LLAS classes (overall classification accuracy was 71%). With classes pooled as suitable (Classes 1–3) versus unsuitable (Classes 4–5), the LiDAR-based model had 90% accuracy in predicting suitable habitat but only 74% accuracy in predicting unsuitable habitat. Of the 12 parameters included in the model, the top five that had the highest predictive accuracy were all measures of macrohabitat (elevation, distance to the nearest sea, aspect, slope, and topographic ruggedness), and tree-based LiDAR measures generally had lower individual predictive accuracy. Measures that involved tree height (individual tree height, height of the 85th LiDAR percentile, average height of all trees above the 85th percentile, and canopy closure) all had individual predictive accuracy below 30%, and only rugosity (measure of canopy surface roughness) had 30% accuracy. In contrast, Hagar et al. (2014) and Hagar et al. (2018) found that maximum canopy height (indicative of the oldest, dimensionally complex stands) was the strongest single predictor of occupancy in the Oregon Douglas-fir forests. This difference between the studies might be due to differences between the range of forest ages included; Clyde (2017) excluded areas, including young regenerating forest, that were obviously not nesting habitat.

Although Clyde (2017) concluded that her LiDAR-inclusive algorithm was a reliable tool for classifying murrelet habitat, her results do not provide strong evidence that LiDAR-based measures are superior to those from other sources, such as LLAS and API. However, her LiDAR-based model was being compared with polygon-based LLAS, which are known to have lower reliability in correctly classifying murrelet habitat than more intensive patch-based LLAS (Burger et al. 2018).

Perhaps the most valuable result from Clyde's (2017) study was her test of whether object-based LiDAR measures (i.e., characterizing individual trees) could be used to identify small patches of suitable habitat (individual trees or clusters of trees) within polygons that were classified by polygon-based LLAS as unsuitable. Clyde (2017) showed that when object-based habitat predictions were averaged across polygons, they had 65% agreement with the original polygon-based LLAS classes, but when the highest object-based predictors (i.e., estimates of larger and more suitable individual trees) were compared, there was only 15% agreement. In the latter case, of 458 polygons that were ranked by polygon-based LLAS as unsuitable (Classes 4 and 5), the object-based LiDAR measures found suitable trees or clusters of trees within 365 polygons (79.7%; based on data in Clyde 2017, Table 4.8). In other words, LiDAR-based predictors were able to identify small patches or individual trees within the polygons that the polygon-based LLAS had classed as unsuitable. The potential for LiDAR to identify small clusters of suitable trees within otherwise unsuitable polygons deserves further testing.

One other potential benefit of LiDAR that Clyde (2017) did not have time to test was the grouping of individual trees into habitat patches (or habitat polygons). Air photo interpretation and LLAS use underlying VRI polygon boundaries to guide the creation of habitat polygons, which is in part why smaller patches of suitable habitat get averaged out into larger polygons. Because LiDAR is object based, individual trees and the associated attributes (as defined by the buffer around the tree) can be grouped together according to values chosen by the end user. This allows one to generate the habitat patch based on the individual matching "objects" or elements, and if desired, without predefining maximum size and shape (as done using LLAS and API). In this latter case, the habitat patch and habitat polygon are equivalent. This approach would provide an alternative method of creating maps of suitable habitat polygons based on individual suitable trees.

LiDAR has the same limitation as API in that platform availability currently cannot be assessed. Therefore, fine-resolution, intensive LLAS or ground surveys will still be required to confirm the presence of platforms at sites. At present, ground-based human observations or LLAS are the only widely used methods that do this (RIC 2001; Burger, Smart, et al. 2004), although drones provide some potential (Murphy et al. 2018[12]; see Section 2.2.2, *Unmanned Aerial Vehicles*). There is some indication that airborne LiDAR, while better than satellite imagery, it is not as good as aerial photos in picking out the big trees with large crowns (K. Nelson, Oregon State Univ., pers. comm.). LiDAR is potentially less expensive and more readily applied to large tracts of forest than is API, especially if forest managers are obtaining high-resolution LiDAR for other purposes (e.g., timber volume).

For further research, at least four avenues need to be explored:

1. Test LiDAR measures and develop resource-selection functions, including LiDAR-based variables at known nest sites (compared to randomly selected sites or sites that are known to be in similar forest but are considered unsuitable). This approach has been very successful in assessing other methods in British Columbia, specifically LLAS and API (see Burger et al. 2018).
2. Investigate if habitat patches (and polygons) of contiguous similar habitat can be generated by grouping individual trees (and associated structure) identified from LiDAR, and how they compare (in size and shape) to predefined polygons generated from LLAS/API or other classifications.
3. Further test the ability of LiDAR metrics to correctly identify small patches of suitable habitat within larger polygons classified as unsuitable by polygon-based LLAS or other coarse-scale methods. Clyde's (2017) study included only watersheds on northern Vancouver Island. Include additional testing in different regions and ecological zones (e.g., Sunshine Coast, southwest Vancouver Island, and the drier forests of the East Vancouver Island Conservation Region).
4. Compare LiDAR with API and LLAS as tools for reliably identifying small patches of suitable habitat within polygons classed as unsuitable on average.

All analyses should include the costs of each method, if possible.

12 Murphy, R.F., E.T. Manning, and B. Schroeder. 2018. An evaluation of utilizing UAVs to assess Marbled Murrelet habitat. Can. Wildl. Serv., Delta, B.C. Unpubl. rep.

In addition, consideration should be given to complementing LiDAR and the established API and LLAS methods with new technological tools as they become available. Ground-based LiDAR might reveal platforms, and is currently being tested (K. Nelson, Oregon State Univ., pers. comm.). Clyde (2017) discussed the potential for new Structure-from-Motion to provide more detailed canopy imagery. Structure-from-Motion is a low-cost photogrammetry method that generates 3-D images from overlapping images at different angles. One of its limitations is that it does not perform as well as LiDAR in denser forest canopies.

Unmanned Aerial Vehicles

Use of drones to locate nests – Oregon State University (J. Rivers and K. Nelson) is in the midst of a comprehensive project that is testing several new technologies for studying Marbled Murrelets.[13] This includes testing unmanned aerial vehicles mounted with a FLIR (brand name) thermal infrared camera to look for the heat signature of the bird sitting on the nest.[14] To date, no Marbled Murrelet nests have been found in Oregon using this technique. Limitations to using drones have included the following:

- The U.S. Fish and Wildlife Service's drone permit allows only 1 hour of flying time near a nest tree per day.
- Unmanned aerial vehicle batteries limit individual trials to about 15 minutes (K. Nelson [Oregon State Univ., pers. comm.] mentions this as a serious limitation because frequent battery changes are required and search time is lost).
- High winds ground the drones.
- Sunlit patches create false positives that mimic the heat signatures of birds.
- Drones are noisy and might disrupt breeding murrelets.

Use of drones to assess canopy microstructure – Murphy et al. (2018) tested the ability of UAVs to assess canopy microstructures and the presence of potential nest platforms for murrelets in the Tsitika Valley, Vancouver Island. The authors' preliminary conclusions, based on relatively limited testing, were that high-quality photo images of canopies and platforms could be obtained from drones, which corroborated or augmented ground-based visual assessments (the standard RIC 2001 protocol). However, the authors recommended the use of UAVs for only small-scale (< 10 ha), high-resolution canopy overview and mapping because restricted flight times (15–20 min), the need to maintain visual contact with the drone in a complex forested habitat, and maximum heights the drone can be flown can all limit the ability to use UAVs to cover large contiguous forested areas, which are not easily accessed by road or on foot (B. Schroeder, consultant, pers. comm.). Murphy et al. (2018) concluded that UAV surveys do not yet provide a viable substitute for ground-based or low-level helicopter-based visual surveys, although UAVs combined with LiDAR might confirm the availability of platforms.

Further testing of UAVs seems necessary, and in theory, the methods used for LLAS with helicopters (Burger, Smart, et al. 2004) might be adapted for UAVs. Drones are being used for many forest-based surveys of a similar nature (Banu et al. 2016; Torresan et al. 2017; Matese 2019). This includes drones fitted with LiDAR or photogrammetry devices (e.g., Wallace et al. 2012). With rapidly

13 https://www.oregonmurrelet.org/technology/.
14 https://www.youtube.com/watch?v=C3DE5AJbfLY.

advancing technology, it is highly likely that UAVs will, in the near future, be advanced enough to provide a useful research and monitoring tool in forested nesting habitat.

Overall comments on drones – It seems prudent to let the well-funded Oregon State University project do the testing of UAVs and to learn from their experiences. If the technology proves useful and the limitations can be worked out, it might be worth applying this method in selected areas where information on small patches is important; for example, on East Vancouver Island, where habitat is rapidly dwindling.

A British Columbia–based company (Sky Pilot Unmanned Aerial Systems)[15] is developing a range of wildlife services using UAVs. Dr. Thor Veen of Quest University in Squamish,[16] one of Sky Pilot's science advisors, currently has a student working on thermal imagery for detecting birds, but this appears to be in an early stage of testing.

2.2.3 Understanding recruitment of nesting habitat from regenerating forest

Recruitment of suitable nesting habitat through the maturation of older regenerating forest is part of the long-term strategy to increase and maintain nesting habitat in areas that are depleted below the recommended recovery amounts, especially in the East Vancouver Island Conservation Region (BCMFLNRORD 2018). Long et al. (2011) modelled the recruitment of suitable habitat to offset losses by logging in each of six Marbled Murrelet conservation regions. They considered recruitment over a 30-year period if forests crossed the threshold to > 250 years old (Model 1) or > 140 years old (Models 2 and 3) and they also met other habitat suitability measures (e.g., distance to the sea, elevation), depending on the model. In the 1978–2008 period, recruitment of habitat was only 2–5% of the area lost to logging in the East Vancouver Island Conservation Region (Long et al. 2011, Table 3), indicating that there needs to be a large increase in recruitment to meet the Recovery Strategy's objectives (Environment Canada 2014). The variation among Models 1, 2, and 3 also emphasized that it often is not known at what age forests 140+ years old become viable nesting habitat for murrelets, particularly if the 140- to 250-year-old stands had suitable platform trees that were retained from the original disturbance (e.g., fire, slides). Tomlins and Gray (2006) and Sutherland, G.D. et al. (2016) used similar approaches to model recruitment of murrelet habitat as part of their analyses of habitat change in the Sunshine Coast and Soo Timber Supply Areas, respectively.

Sutherland, I.J. et al.'s (2016) analysis of data from 49 study plots in CWHvm1 forests (one of the BEC variants most commonly used by murrelets) on Vancouver Island provided useful information on likely rates of habitat recruitment in regenerating forests. Recruitment of suitable platforms for Marbled Murrelets, based on analysis of presence or absence, was one of the explicit metrics in this study. The probability of platform availability showed a non-linear logistic-like increase with forest age, and reached probabilities similar to the mean for old-growth forest at the end of the age series (212 years old). Of equal value, the study showed that at age 140 years (the threshold for age class 8 in forest cover data: 140–250 years), the probability of trees providing suitable platforms was only 0.28 (28%; 95% confidence limits 0.18–0.39) (Sutherland, Bennett, et al. 2016,

15 http://skypilotuas.com/.
16 thorveen@gmail.com.

Figure 2). Many management and inventory applications consider age class 8 as a threshold for possible suitable murrelet habitat, based on the Marbled Murrelet Recovery Team recommendations (CMMRT 2003). Sutherland, I.J., et al. (2016) indicated that at 140 years, very few platforms are likely to be provided, but there is a steep increase in availability between 140 and 212 years of age. This analysis has relatively limited power to apply these predictions to a wider range of ecosystems and was based on relatively small samples of platform trees (only seven plots appeared to provide suitable platforms). Similar analyses that cover a wider range of regions and BEC zones and subzones would provide greater confidence in predicting recruitment of suitable habitat in regenerating forest. Such analyses would also provide stronger guidance on when to accept age class 8 as suitable habitat.

Waterhouse et al. (2002) developed resource selection functions from air photo interpretation to predict the habitat at actual nest sites on the Sunshine Coast (Southern Mainland Coast Conservation Region). Vertical complexity best predicted which polygons murrelets used for nesting and which were likely to have had a successful nest (to midway in chick development). In order to predict habitat recruitment, the authors also compared vertical complexity with stand age. In moderate to non-uniform stands (with the highest vertical complexity), the conditional probability of a polygon having a nest continued to increase up to age 400 years. The probability that the nest would be successful showed a similar trend but increased at progressively lower rates after about 250 years. In more uniform stands (with lower vertical complexity), the probabilities of a nest being present or that the nest would be successful were both much lower than in higher-complexity stands, even at ages 200–300 years. The authors suggested that age was probably a surrogate for microhabitat features such as platform size and amount of epiphyte cover. They also indicated that managing younger stands to enhance vertical complexity could potentially restore habitat quality for murrelets at an earlier age than stands that are uniformly managed.

Burger et al. (2010) analyzed the availability of potential nest platforms relative to the diameter at breast height (dbh) of trees in British Columbia using data from six conservation regions. The findings showed significant regional variability and differences among the common forest tree species. These data might be applied to age-dependent recruitment estimates, using regressions of dbh versus tree age, although the regressions are also likely to be affected by macrohabitat and microhabitat features. Research into possible methods of accelerating recruitment of suitable habitat (e.g., thinning trees, inoculating canopy boughs with bryophytes, creating gaps in dense mature forests) has not been undertaken with murrelets in mind, but D'Anjou et al. (2015) used a similar approach in Spotted Owl (*Strix occidentalis*) habitat. Such adaptive management might be useful in specific landscape units of the East Vancouver Island and Southern Mainland Coast Conservation Regions where suitable habitat is lacking.

Additional useful information on changes in canopy structure and limb diameter with tree age are available for some conifer species that are used by nesting murrelets (Ishii and McDowell 2002; Nemec et al. 2012). The Tree And Stand Simulator used by the FLNRORD Forest Analysis Branch to project future timber volumes could be modified to include older forests (the original model cut-off was 80 years to match harvest rotations) and a wider range of scenarios (including forest gaps) to help predict recruitment of murrelet habitat. This approach is being used to study recruitment of Spotted Owl habitat in British Columbia (F.L. Waterhouse, FLNRORD, pers. comm.).

2.3 Ongoing and Likely Future Factors Affecting Marbled Murrelets

2.3.1 Climate change influences on murrelet habitat availability and distribution Understanding changes in the ecosystems and forests that support murrelet nesting is important, especially in assigning protected areas for long-term maintenance of breeding populations. Existing and planned reserves, such as parks and WHAs, might become unsuitable as climates, forests, marine foraging conditions, and murrelet distributions change.

Likely changes to climates in coastal British Columbia – Substantial changes in climate envelopes (dominated by temperature and precipitation effects), optimal growing conditions for dominant forest trees, and areas that favour the major biogeoclimatic zones are predicted to occur within the next 50–80 years. Models generally report on likely changes in the 2020s, 2050s, and 2080s. For the coastal regions of British Columbia, the following changes are expected in the 2050s, relative to baseline measurements 1961–1990 (Shanley et al. 2015; Price and Daust 2016[17]):

- summer temperatures will rise by 1.5%
- winter temperatures will rise by 1.3%
- summer precipitation will fall by 16%
- winter precipitation will rise by 6%
- winter snowfall will decline by 28%
- spring snowfall will decline by 52%
- risk of wildfires will increase
- effects of wind on forests will increase
- risk of insect outbreaks may increase, but this is not certain

Summer moisture deficits are expected to increase in southern and coastal regions of British Columbia (Spittlehouse 2008; Morgan and Daust 2013[18]; Marlier et al. 2017). Changes will be less marked in coastal British Columbia than in the Interior (Shafer et al. 2015; British Columbia Auditor General 2018). Most coastal lowlands will remain wet, and Haida Gwaii and northern coastal areas are expected to change the least (Shafer et al. 2015; Shanley et al. 2015), although not all climate models give the same predictions (DellaSala et al. 2015).

Likely changes to biogeoclimatic zones and tree species distributions – Based on predicted changes in climate envelopes, several studies have predicted changes in the distribution and viability of biogeoclimatic zones and individual tree species. In all of these predictions, researchers caution that tree distribution and viability are not mediated only by climates — soils, aspect, microhabitats,

17 Price, K. and D. Daust. 2016. Climate change vulnerability of BC's fish and wildlife: first approximation. B.C. Min. For., Lands Nat. Resource Ops., Competitiveness and Innovation Br., Victoria, B.C. Unpubl. rep. https://www2.gov.bc.ca/assets/gov/environment/natural-resource-stewardship/nrs-climate-change/adaptation/climate20change20vulnerability20of20bcs20fish20and20wildlife20final20june6.pdf.

18 Morgan, D. and D. Daust. 2013. A climate change vulnerability assessment for British Columbia's managed forests. B.C. Min. For., Lands Nat. Resource Ops., Competitiveness and Innovation Br., Victoria, B.C. Unpubl. rep. https://www2.gov.bc.ca/assets/gov/environment/natural-resource-stewardship/nrs-climate-change/applied-science/1_va_intro20final20sept11.pdf.

and the ability of trees to migrate are all important factors. Some studies clearly focussed on predicting the optimal species and genetic variants for silvicultural planting (e.g., Gray and Hamann 2012). In addition, the predictions cover approximately the next 50–100 years, whereas it takes about 200 years to produce trees that are suitable for nesting habitats (Burger et al. 2010; Sutherland, I.J., et al. 2016). Therefore, the predictions are only rough approximations of how Marbled Murrelet forest habitat might change in the next 50–80 years.

In general, by the 2050s, climate envelopes will likely move upward in elevation by 300 m and farther north by 170 km. Most Marbled Murrelets in British Columbia nest in the CWH zone. Conditions that favour this zone are predicted to expand considerably in the coming 50–70 years (Table 1); CWH drier variants would expand at lower elevations and replace wetter variants as they in turn expand upward into the Mountain Hemlock zone. Fewer murrelets nest in the CDF zone, which is expected to initially decline slightly but later expand considerably as the climate warms (Table 1). Some murrelets nest in the high-elevation Mountain Hemlock zone, which is expected to decline through the coming 50–70 years, likely to be replaced by conditions that favour the maritime CWH forests (Hamann and Wang 2006; DellaSala et al. 2015).

TABLE 1 *Predicted change in the areas suitable for the major biogeoclimatic zones in which Marbled Murrelet primarily nest (from Wang et al. 2012; modified by Price and Daust 2016)*

		Change in climate habitat (% loss or gain)		
Biogeoclimatic zone	**Area (1000 ha)**	**2020s**	**2050s**	**2080s**
Coastal Western Hemlock	10 800	+22	+40	+69
Coastal Douglas-fir	200	−1	−3	+19
Mountain Hemlock	3 600	−4	−7	−12

Looking purely at the conditions that favour these most-used BEC zones, it appears that climate change might not have major deleterious effects on nesting Marbled Murrelets in British Columbia. In general, the total areas of coastal coniferous forests are likely to remain stable in distribution through 2050 to 2070, with perhaps some reductions on Haida Gwaii and a few other parts of the coast (DellaSala et al. 2015).

Climate-driven changes in the viability and distribution of major tree species have also been predicted in several studies (Hamann and Wang 2006; Gray and Hamann 2012; DellaSala et al. 2015). These changes are reviewed (Table 2), taking into consideration the frequency of use of the various tree species by nesting Marbled Murrelets (Nelson 1997; Burger 2002; McShane et al. 2004; Simon Fraser University, unpubl. data) and the probabilities of those tree species providing suitable nesting platforms at various ages and tree diameters (Burger et al. 2010). The distribution of optimal habitat (based on climatic effects, and excluding the effects of topography and soils) for many coastal conifer species has already shifted since the 1960s, and will continue to shift in elevation and latitude with changing climates (Hamann and Wang 2006; Gray and Hamann 2012; DellaSala et al. 2015).

In summary, predicted climate changes are likely to favour two of the tree species that are commonly used by Marbled Murrelet in British Columbia (e.g., western hemlock, Sitka spruce), one species that is used less frequently

TABLE 2 *Predicted changes in the distributions and viability of tree species used for nesting by Marbled Murrelets in British Columbia*

Tree species	Importance to nesting Marbled Murrelets[a]	Expected changes[b]	Notes
Western hemlock	Widely used in CWH[c]	Increase	Some models predict a 50% expansion in distribution (DellaSala et al. 2015).
Mountain hemlock	Used in high elevations, MH[c] (few nests)	Decrease	Likely to disappear from some high-elevation areas.
Western redcedar	Regularly used but not ideal (narrow sloping branches)	Decline in some areas and stable or increase across a wider range	Decline expected on east Vancouver Island (Seebacher 2007) but stable or increase across the wider range.
Yellow-cedar	Highly favoured—mostly higher-elevation MH and in central and northern areas	Decrease	Already declining in the north due to reduced snowpack (Hennon et al. 2012).
Sitka spruce	Highly favoured—mostly valley bottoms, CWH	Stable or increase	Holliday et al. (2012) suggested that movement of warm-adapted alleles from the south may enhance adaptation to new northern habitats.
Douglas-fir	Favoured in CDF[c] and drier CWH areas but not ideal (often few mossy pads)	Stable or increase, although some evidence of recent die-offs	Chen et al. (2010) predicted that climate change effects are likely to be overall neutral for coastal Douglas-fir varieties.
Grand fir	Not widely available or used	Decrease	
Amabilis fir	Used in CWH and MH but not ideal (narrow branches)	Decrease	
Red alder	Very few nests	Increase	Broad-leaved woodland is expected to expand and perhaps replace conifers in some parts of coastal British Columbia (DellaSala et al. 2015).

a Based on frequency of actual nests in British Columbia (Burger 2002; Simon Fraser University, unpubl. data) and on the probabilities of providing suitable nest platforms (Burger et al. 2010). Tree species used in Washington were also considered (McShane et al. 2004).

b Based on Hamann and Wang (2006), Chen et al. (2010), Gray and Hamann (2012), Holliday et al. (2012), and DellaSala et al. (2015). Note that not all climate modelling gave the same predictions for some species.

c CWH: Coastal Western Hemlock biogeoclimatic zone; MH: Mountain Hemlock biogeoclimatic zone; CDF: Coastal Douglas-fir biogeoclimatic zone.

(Douglas-fir), and one very rarely used species (the deciduous red alder). Climate changes are predicted to have negative effects on two favoured species (mountain hemlock and yellow-cedar — more likely in high elevations) and on less frequently used species (amabilis fir and grand fir). The effects of climate changes on western redcedar seem more complex than on other species. There is already die-off associated with warmer, drier summers on Vancouver Island, and this species' population is expected to decline in low-elevation dry habitats on the Island (Seebacher 2007; Pojar 2010). Climate envelope modelling, however, predicts more stable populations over the broader British Columbia and Pacific Northwest range, with a >20% probability of increase by 2050–2080, and a shift to higher elevations (Hamman and Wang 2006; Gray and Hamman 2012; DellaSala et al. 2015). Climate envelope modelling might not take into account the effects of diseases or other stressors being mediated by climate change. For example, some localized die-off of Douglas-fir has been reported, perhaps linked with disease, even though warming climates are thought to favour this species.[19]

19 https://bcitnews.com/2019/05/15/western-red-cedar-is-just-one-of-many-bc-trees-facing-extinction/. https://extension.oregonstate.edu/forests/health-managment/stressed-trees-show-dieback.

As noted, murrelets primarily use trees > 200 years old, and the climate models do not predict widespread mortality of currently living trees (with the exception of northern populations of yellow-cedar) (Hennon et al. 2012). It should not be expected, therefore, that climate-driven changes in optimal conditions for tree species will have strong effects on Marbled Murrelets within the next 50–80 years. Future effects will be strongest in the long term after stable, currently suitable habitats are disturbed by natural or resource development events and species shift in the recovering areas. In the short term, habitat loss and fragmentation that produce higher edge densities and in turn affect site microclimates are likely to have far greater effects on British Columbia murrelet nesting habitat than changes that affect BEC zones and common tree species abundance.

The frequency and severity of catastrophic events, such as forest fires (Marlier et al. 2017), and landslides and flooding triggered by more intense rainfall events, are also likely to be affected by climate change in coastal British Columbia, although the effects are expected to be less than in the British Columbia interior (Morgan and Daust 2013; British Columbia Auditor General 2018). It is difficult to predict at present how such catastrophic events might affect murrelet nesting habitat. Identification of high-risk areas might help avoid locating important protected forest habitat (e.g., WHAs) in areas that are likely to be affected by future climates.

Likely changes affecting canopy microhabitats – Many studies have investigated the effects of climate change on forest trees and biogeoclimatic zones, but few have considered the changes that might occur within forest canopies. Canopy epiphytes, predominantly bryophytes (mosses and liverworts), and to a lesser extent lichens, currently provide most of the suitable nest platforms for murrelets in British Columbia (Burger et al. 2010). The drier and warmer summers and increased wind that are predicted in British Columbia's coastal areas are likely to affect the growth and persistence of bryophytes. In general, bryophytes are more sensitive to changes in air humidity and precipitation (i.e., water availability for growth) than to temperature changes, and therefore do not necessarily respond to climate change in the same way as vascular plants (Gignac 2001; Tuba et al. 2011; He et al. 2016; Marschall 2017; Scarpitta et al. 2017). Epiphytic bryophytes, in particular, are highly sensitive to exposure to sun and drying conditions; this affects their growth more than their survival (Gignac 2001; Marschall 2017). Climate change effects on canopy bryophytes have not received much attention (Tuba et al. 2011), although epiphytic lichens (not a major component of murrelet nest platforms) have been considered useful indicators of climates and environmental conditions (Aptroot 2009; Ellis et al. 2014). Major reviews and models of how climate change might affect forest vegetation in the Pacific Northwest have not considered canopy epiphytes or any bryophytes (e.g., Morgan and Daust 2013; Peterson et al. 2014).

Warmer and drier summers, coupled with increased winds that are expected in the future in coastal British Columbia, are likely to increase desiccation and inhibit growth and survival of epiphytes. Increased exposure to wind is also likely to increase physical damage to, and removal of, canopy epiphytes. These processes have far greater negative effects at forest edges than in interior forest (Burger 2016; Raphael et al. 2018). With warmer, windier summers in coming decades, these deleterious edge effects are likely to penetrate deeper into interior forests than at present.

Understanding the likely changes in epiphytic mossy platforms across the Marbled Murrelet's range and establishing baseline data for monitoring future changes seems to be a worthy priority, especially at forest edges and in the areas of southern British Columbia where moister CWH forests are likely to be replaced by conditions that favour drier ecosystems (e.g., CDF or CWHxm biomes). In Douglas-fir forests, murrelets sometimes nest on large limbs that have a litter/duff layer (Nelson 1997; McShane et al. 2004). Understanding limb development (e.g., Ishii and McDowell 2002; Nemec et al. 2012) and duff accumulation in CDF forests would aid long-term planning of murrelet reserves in some southern areas of British Columbia.

Estimates of platform availability made during ground surveys (e.g., database managed by FLNRORD, Ecosystems, West Coast Region) and LLAS provide some historical baselines that should also be explored. The use of drones might provide affordable quantitative measures of mossy platform availability (see Section 2.2.2, *Unmanned Aerial Vehicles*). The existing LLAS protocols (Burger, Smart, et al. 2004) might need some modification for drone surveys.

2.4 Population Dynamics, Demographic Rates, and Genetics

2.4.1 Population demography and vital rates of Marbled Murrelets in British Columbia Intrinsic factors that affect murrelet population growth will interact with habitat factors to affect overall population-level effects. Information on population demography and vital rates of murrelets in British Columbia is limited to data collected in one geographic region (Desolation Sound) in 1991–2000 (Lougheed 2000; Cam et al. 2003). Throughout the rest of the province, there has been no estimate of rates of survival, fecundity and breeding propensity, immigration/emigration, or juvenile dispersal, and how these factors could interact with other pressures on the population to influence overall population trends and habitat use. Demographic data are likewise lacking for the U.S. portion of the species' range, except for central California (Peery, Beissinger, Newman, et al. 2004; Peery, Beissinger, Burkett, et al. 2006; Peery, Becker, et al. 2006; Peery, Beissinger, House, et al. 2008), although the current Oregon Marbled Murrelet Project[20] should provide demographic data.

2.4.2 Philopatry Current understanding of philopatry in murrelets remains limited. Movement of murrelets between watersheds or subregions or across regions in response to habitat conditions, either marine or terrestrial, is poorly understood but is suspected to contribute to annual regional changes in abundance that have been observed by using radar (Bertram et al. 2015). For example, it is unclear whether individuals move in response to poor marine conditions then return to their natal watersheds when conditions improve. Evidence of variable site fidelity at the nest site and nest tree (low fidelity where suitable trees are abundant and high fidelity where such trees are sparse) has been documented (Burger et al. 2009), but at the population level, it is not known how these patterns affect murrelet abundance and distribution at various spatial scales. The Desolation Sound study showed that the rates of emigration were high for newly fledged hatch-year birds, while the adult population had low rates of emigration and immigration (Lougheed 2000; Cam et al. 2003). More recent satellite telemetry has recorded relatively common long-distance (hundreds of kilometres) movements of post-breeding adults in a northward direction (Bertram et al. 2016; D. Bertram, Environment and Climate Change Canada,

20 https://www.oregonmurrelet.org/.

unpubl. data). Potential population source–sink dynamics have not been explored in British Columbia. Watersheds with large areas of remaining suitable habitat adjacent to productive marine habitat may act as source populations from which individuals disperse to neighbouring areas. These dynamics could mask underlying effects of habitat fragmentation, predation, or poor marine conditions in population sinks. Areas identified as source populations may also be more important to prioritize for habitat protection.

2.4.3 Population genetics and genetic divergence Information on population genetic structure and local adaptive genetic divergence in British Columbia is limited. Friesen et al. (2005) found that British Columbia murrelets were lumped with mainland Alaska murrelets into one population unit based on neutral genetic variation in mitochondrial DNA. More recent analyses have shown that major histocompatibility complex class II B genes can be used to improve the delineation of murrelet conservation units by identifying populations that harbour local adaptations (Vasquez-Carrillo et al. 2014), but these analyses have not been performed on samples from British Columbia. Over time, as more genetic samples are collected, it would be worth exploring the genetic diversity of British Columbia populations, particularly smaller, declining populations. The recent major histocompatibility complex class II B gene analysis compared alleles and inferred peptides from Alaska, Oregon, and California populations, and showed that although the Oregon population was larger than the California population, it had likely experienced pathogen-mediated natural selection that resulted in reduced diversity of the alleles. This could make the population more susceptible to novel diseases or pathogens. The implications of such genetic bottlenecks need to be considered in British Columbia, especially in the Salish Sea populations, where there is evidence of major population declines in the past century or more (Burger 2002; Gutowsky et al. 2009). Understanding genetic variability helps in interpreting immigration, dispersal, and source–sink dynamics of Marbled Murrelets and whether terrestrial habitat management alone can maintain long-term murrelet populations (Hall et al. 2009; Vasquez-Carrillo et al. 2013).

3 PROPOSED STUDIES AND RESEARCH PRIORITIES

This section draws upon the knowledge gaps identified in Section 2 and integrates them to identify priority terrestrial research questions for FLRNRORD to consider. Table 3 lists potential research questions based on the knowledge gap analysis. The studies are not listed in any priority order, and some may address multiple knowledge gaps.

TABLE 3 *Potential research studies to address knowledge gaps for Marbled Murrelet terrestrial habitat management*

Research question	Study objectives	Conceptual approach	Comments	Links to report sections
Is nest site selection and nesting density in northern British Columbia similar to that in the southern British Columbia area, and what implications might this have for habitat quality classification and mapping?	1. Expand the range of known nest sites in British Columbia to include two regions that support large numbers of nesting murrelets (Northern and Central Mainland Coast Conservation Regions [see Environment Canada 2014]). 2. Further develop regional models of habitat use for these areas. 3. Expand the range of data to test habitat identification methods coast-wide. 4. Use nearest neighbour methods with acoustic recording units (ARUs) to estimate density per stand.	Locate nest sites in the Northern and Central Mainland Coast Conservation Regions using standard radio telemetry or satellite tracking. This involves: • follow-up nest discovery with air photo interpretation (API) and low-level aerial surveys (LLAS) of habitat (and possibly LiDAR). Inland radar studies focussed on identifiable stands to determine murrelet use could be an alternative approach if telemetry is not feasible.	Use of telemetry would be expensive, likely costing several hundred thousand dollars and requiring 2–4 years, based on Simon Fraser University (SFU) experience in Desolation and Clayoquot Sounds. Previous work at Mussel Inlet on the mid-coast proved challenging (Kaiser and Keddie 1999[a]), although more recently in Alaska, Kissling et al. (2015) found many Kittlitz's Murrelet nests and Barbaree et al. (2014) found Marbled Murrelet nests, including a nest in British Columbia in Conservation Region 7 (Alaska border). Deployment of GPS radio-tags and satellite platform terminal transmitters (PTT) tags could reduce the costs of tracking tagged birds, but the current resolution of these devices and their effects on murrelets does not recommend their use at this time (see Section 2.2.2). Improvements in device size and spatial resolution should allow these devices to be used in the future. Research on tag development and attachment methods is under way.[b]	2.1.1 Determining regional variation in nest sites and habitat 2.1.2 Understanding the relationship between habitat quality and nesting density 2.2.2 Testing new technologies to improve habitat identification, classification, and mapping
How does the diet of breeding murrelets vary coast-wide in British Columbia, and what are the potential implications for habitat management adjacent to marine foraging areas?	1. Isotope analyses of feces and feathers from nests (see previous research question) will add to the sparse knowledge about diets in British Columbia. 2. Understanding diet in combination with location data from telemetry can provide a more complete picture of foraging strategies based on trophic level and the potential limiting effects of prey on habitat use and reproductive success.	Analyze stable isotopes in feces and feather samples from previously discovered nests (e.g., Manley 1999; SFU and University of Victoria [UVIC] samples) and nests discovered in new research to identify diets.	Studies of stable isotopes in feathers and other tissues have revealed much about the diets (past and present) and population status of murrelets (e.g., Hobson 1990; Hobson et al. 1994; Norris et al. 2007; Gutowsky et al. 2009; Janssen et al. 2009, 2011).	2.1.5 Linking marine and terrestrial factors affecting Marbled Murrelets

a Kaiser, G.W. and G.A. Keddie. 1999. Locating nest sites of the Marbled Murrelet: a pilot project in radio telemetry on the central coast of British Columbia. Can. Wildl. Serv., Delta, B.C. Unpubl. rep.
b M. Kissling (PhD research), University of Montana, W.A. Franke College of Forestry and Conservation, Missoula, Mont.

Research question	Study objectives	Conceptual approach	Comments	Links to report sections
How do murrelet habitat requirements and distribution vary by biogeoclimatic unit, and what are the implications for habitat management?	1. Improve the accuracy of range-wide and regional habitat mapping algorithms. 2. Determine if habitat use and distribution and/or selectivity (if measuring availability) changes among regions or biogeoclimatic units. 3. Estimate relative abundance per stand per biogeoclimatic unit by survey method.	Compare habitat characteristics of active stands among conservation regions and biogeoclimatic units. This involves: • sampling range-wide Marbled Murrelet activity with audio-visual (AV) or ARUs and/or radar (including inland radar) to identify suitable stands/local landscapes/watersheds and measure habitat attributes and stand condition in order to compare among sites.	Donald et al. (2010) found that API underestimated habitat quality (as assessed with LLAS) in some areas on the Central Coast but overestimated quality in other areas; this appeared to be due to the influence of hypermaritime climates. Expand historic data set (e.g., the Marbled Murrelet consolidated database— FLNRORD, Ecosystems, West Coast Region).	2.1.1 Determining regional variation in nest sites and habitat 2.2.1 Reliable identification of nesting habitat (improving habitat predictors) 2.1.2 Understanding the relationship between habitat quality and nesting density
Does the relationship between platform availability relative to tree size change coast-wide with biogeoclimatic unit? And how does that affect nesting density/habitat capability?	1. Improve the accuracy of range-wide and regional habitat mapping algorithms. 2. Provide a wider range of data for analyzing platform development relative to tree size and age.	Improve regional predictions of suitable habitat by expanding the original Burger et al. (2010) approach coast-wide. This involves: • increasing the ground sampling of vegetation plots, focussed on platform availability relative to tree size, species, BEC site series, etc. • developing regional and species-specific regressions to convert diameter at breast height (dbh) (as used by Burger et al. 2010) to tree age to better understand platform recruitment phenology. • using AV or ARUs to test the presence of, and occupancy by, murrelets, and to provide additional value to habitat sampling.	Data on platform development that were available to Burger et al. (2010) were based on limited sampling in the Northern Mainland Coast and Central Mainland Coast Conservation Regions. Sutherland, I.J. et al. (2016) sampled only in the Coastal Western Hemlock[CWH]vm1 on Vancouver Island. Sampling of trees in the drier biogeoclimatic units (e.g., CWHxm and Coastal Douglas-fir [CDF]) would also improve understanding of platform development where moss is scarce. Sample areas classified by LLAS or API to confirm relationships between platform abundance and these classifications.	2.1.1 Determining regional variation in nest sites and habitat 2.2.1 Reliable identification of nesting habitat (improving habitat predictors) 2.2.3 Understanding recruitment of nesting habitat from regenerating forest

Research question	Study objectives	Conceptual approach	Comments	Links to report sections
What is the predicted relationship between loss and fragmentation of nesting habitat and the decline of Marbled Murrelet local populations?	1. Quantify the relationship between loss and fragmentation of nesting habitat and the decline of Marbled Murrelets. 2. Separate the effects of habitat area and habitat fragmentation. 3. Determine if harvest pattern and habitat distribution over time influences murrelet abundance; that is, develop spatially explicit habitat supply modelling.	Determine if change in landscape condition affects murrelet relative abundance over time: • Use inland radar and metrics that characterize change in landscape structure and amount of suitable habitat in watersheds, and conduct repeated long-term sampling to test.	Power analysis (Arcese et al. 2005)[c] indicated that large-scale habitat change is needed to detect change in radar counts of murrelets. Watersheds in which long-term radar monitoring and different levels of areas disturbed by resource development have occurred can be compared to test. Analysis could use radar data from the Environment Canada database (D. Bertram, Environment and Climate Change Canada, pers. comm.) plus additional radar surveys, combined with habitat changes from harvesting. Work on this project is being conducted by FLNRORD, and includes habitat loss calculations and radar sampling (J. Cragg and F.L. Waterhouse, pers. comm.).	2.1.2 Understanding the relationship between habitat quality and nesting density 2.1.3 Understanding the effect of landscape condition on site-level occupancy, including the use of small habitat patches
Is there a minimum threshold for suitable habitat patch size to support successful murrelet nest sites, and does it change with landscape condition and the surrounding matrix?	1. Understand the frequency and conditions of murrelets nesting in small patches with hard edges or fragmented landscape. 2. Provide estimates of minimum patch size for Wildlife Habitat Areas (WHAs) and other management. 3. Improve determination of "denominator" suitable habitat area in each region for the ~70% recovery goal.	Examine murrelet use of small habitat patches with hard edges and the influence of landscape condition on site use. Includes testing the application of: • AV and ARU to assess patch use by murrelets; • radar to determine murrelet numbers.	In part, under way by Waterhouse and Cragg (see Cragg et al. 2019). Also see research under Oregon Marbled Murrelet Project.[d]	2.1.3 Understanding the effect of landscape condition on site-level occupancy, including the use of small habitat patches

c Arcese, P., A.E. Burger, C.L. Staudhamer, J.P. Gibbs, E. Selak, G.D. Sutherland, J.D. Steventon, S.A. Fall, D. Bertram, I.A. Manley, S.E. Runyan, W.L. Harper, A. Harfenist, B.K. Schroeder, D.B. Lank, S.A. Cullen, J.A. Deal, D. Lindsay, and G. Jones. 2005. Monitoring designs to detect population declines and identify their cause in the Marbled Murrelet. Univ. British Columbia, Cent. Appl. Conserv. Res., Vancouver, B.C. Unpubl. rep.
d https://www.oregonmurrelet.org/.

Research question	Study objectives	Conceptual approach	Comments	Links to report sections
Can murrelet nesting habitat be reliably identified using habitat attributes described by airborne LiDAR, and if so, will this improve predictive habitat mapping for implementation of spatial management?	1. Assess the utility of LiDAR for habitat management. 2. Understand the frequency and conditions of murrelets nesting in small patches or single suitable trees within an unsuitable forest matrix (not retained trees in clearcuts). 3. Improve determination of “denominator” suitable habitat area in each region for the ~70% recovery goal. 4. Improve habitat models and mapping. Understand patch-level habitat requirements relative to stand-level availability.	Determine if airborne LiDAR identifies murrelet-suitable nesting habitat. • Test habitat selectivity using nest sites and random sites with attributes identified from LiDAR (see Hagar et al. 2014), and the feasibility of using LiDAR to determine patch sizes. • Test if LiDAR identifies the use of single trees or small clusters of suitable trees or small patches within unsuitable habitat matrices defined by LLAS/API/other methods, and use AV surveys, ARU deployment, or tree climbing to confirm site visitation and occupancy.	Nest sites previously located by telemetry could be used for LiDAR-based comparisons with randomly selected sites or the matrix surrounding the nest stand. This work has been initiated in collaboration with the University of British Columbia, FLNRORD, and experts from the Canadian Marbled Murrelet Recovery Team (F.L. Waterhouse, pers. comm.). Expand on Clyde’s (2017) LiDAR study with a wider range of habitats and different regions. This project could address the issues of LiDAR reliability. This study could expand on current research that has been initiated to examine small “patches” with hard edges.	2.1.3 Understanding the effect of landscape condition on site-level occupancy, including the use of small habitat patches 2.2.1 Reliable identification of nesting habitat (improving habitat predictors) – LiDAR 2.2.2 Testing new technologies to improve habitat identification, classification, and mapping
How do murrelet predator populations change or redistribute with habitat fragmentation, and at which stages of stand edge recovery? How does habitat fragmentation affect predator density at the landscape scale? Are predator populations sustained on the landscape by continued harvesting, even as some edges regenerate? What is the relationship between edge density and predator abundance?	1. Improve understanding of predation risk in various stages of fragmentation within British Columbia forests (most predator studies in British Columbia to date have been adjuncts to studies on Marbled Murrelet activities, and few are published). 2. Combine with other measures of predator abundance (e.g., eBird, breeding bird surveys) to assess trends in predator populations and risk to murrelets.	Involves: • monitoring densities of potential predators within Landscape Units in various stages of fragmentation (clearcuts) and recovery (maturing forest); • differentiating changing population densities from changing spatial distributions in fragmented forest; • using ARUs for monitoring relative densities of birds and squirrels, plus point-counts for comparative data.	Could be linked with multi-site or multi-year monitoring of Marbled Murrelet occurrence. The strongest data might come from predator surveys done before harvesting and over 10+ years following harvesting as clearcuts regenerate. Could be linked to studies of Northern Goshawk or other forest-dwelling wildlife species (e.g., SFU study under way).[e] Also see research under way on Steller’s Jay.[f]	2.1.4 Quantifying and managing edge effects and predation

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f K. Brunk (PhD research), University of Wisconsin-Madison, Peery Wildlife Ecology and Conservation Lab, Madison, Wis.

Research question	Study objectives	Conceptual approach	Comments	Links to report sections
How does forest harvesting and edge creation change the growth and persistence of canopy epiphytes that are typically associated with murrelet nesting habitats?	1. Understand factors that determine nest platform availability in different biogeoclimatic conditions. 2. Understand the effects of hard edges on canopy conditions and platform availability. 3. Improve predictions of changes in canopy conditions that are likely with future climate changes.	Involves: • year-round monitoring of microclimates and epiphyte condition within canopies, covering a range of habitat conditions, including hard forest edges; • measuring the depth of edge effects into interior forest, taking into account (a) changing climate, and (b) changes in forest fragmentation; • conducting multi-year sampling to track changes at newly created hard edges bordering fresh clearcuts.	Best applied to studies at forest edges in various stages of regeneration (clearcut to mature forest adjacent to old-growth habitat) to determine the effects of adjacent clearcut logging over time. Will require experienced tree climbers to do the fieldwork, but some sampling might be possible with drones. Could be combined with other canopy studies (e.g., N. Winchester, UVIC, working on canopy arthropods).	2.1.4 Quantifying and managing edge effects and predation
How does proximity to marine foraging areas affect nesting productivity (short and long term)? How does variable marine productivity influence breeding effort and success in adjacent terrestrial nesting habitat.	1. Understand the relative importance of marine vs. terrestrial habitat on population limitation of Marbled Murrelet in different regions. 2. Understand spatial patterns of marine habitat use relative to adjacent terrestrial breeding habitat, and how they differ between conservation regions. 3. Conduct multi-year studies to improve understanding of the effects of climate change and shorter-term oceanic fluctuations (e.g., El Niño/Southern Oscillation, Pacific Decadal Oscillation). 4. Improve understanding of the effects of long commuting distances between nesting and feeding locations (e.g., long fjords in northern regions).	Linking terrestrial and marine factors that are limiting populations and recruitment of Marbled Murrelet. Involves: • combining repeated at-sea surveys with terrestrial measures of murrelet activity (radar, AV, or ARU surveys); • using hatch year : after hatch year ratios at sea to estimate recruitment, taking into account the movement of fledged juveniles and the appropriate spatial scale needed to account for such movements; • considering using radio telemetry or new GPS technology options to determine foraging distances and ranges; • sampling prey availability and abundance concurrently.	Range-wide analysis might be possible when Environment Canada completes the GIS analysis of at-sea distribution. Finer-scale studies would be best applied at two sites that have existing long-term at-sea surveys (Laskeek Bay and Pacific Rim National Park Reserve). Marine sampling in the Salish Sea will be conducted in accordance with the increased monitoring recommended by the National Energy Board to provide baseline information for the Trans Mountain Pipeline expansion. Marbled Murrelet has been identified as a species at risk in this process, but surveys are currently designed to sample systematically for all seabirds, not to sample the nearshore distribution of Marbled Murrelet (C. Fox, Canadian Wildlife Service, pers. comm.). Oregon State University (M. Betts) is completing a similar study that compares AV detections and occupancy with proximity to marine feeding areas and fluctuations in marine productivity.[g]	2.1.5 Linking marine and terrestrial factors affecting Marbled Murrelets 2.2.1 Reliable identification of nesting habitat (improving habitat predictors)

g https://www.oregonmurrelet.org/.

Research question	Study objectives	Conceptual approach	Comments	Links to report sections
How frequently are stands of suitable murrelet habitat re-used for breeding, and does this change with stand size, quality, landscape condition, and adjacency to marine forage habitat? What are the implications for spatial management?	1. Determine the fidelity of nest patch and nest tree use from year to year (important for understanding the value of WHAs for Marbled Murrelet). 2. Understand the relationship between site fidelity and stand habitat quality and size.	Involves repeated measures at selected stands, including: • measures of platform availability (and other habitat attributes); • AV and ARU surveys to determine murrelet use; • use of radar for watershed-level monitoring; future GPS/satellite tagging if technology develops sufficiently.	Evidence of watershed and stand re-use and fidelity reviewed by Plissner et al. (2015). Some testing of stand re-use is being conducted by Waterhouse and Cragg as part of a patch project. May consider revisiting historical telemetry nest locations that were accessible, and using AV or ARU to determine if they are still occupied.	2.1.6 Understanding the importance of site re-use for spatial management
Are UAVs (drones) a useful tool for identifying active murrelet nest sites and sampling for breeding habitat quality?	1. Assess whether drones can replace helicopters for LLAS, and hence, reduce costs. 2. Assess the application of UAVs to locate active or recently used nests. 3. Test current and future devices for fine-scale mapping of canopy structure (e.g., LiDAR, other photogrammetry methods).	Test the application of UAVs (drones) in Marbled Murrelet research. Includes: • testing the assessment of canopy suitability and platform availability; • searching for nest sites (after the breeding season to avoid disturbing nesting birds).	Prudent to collaborate with Oregon State University Marbled Murrelet team (J. Rivers and K. Nelson)[h] to build on their experience. Currently, there is no nest location project in British Columbia to test the ability of drones to locate active nest sites, but drones might be able to locate recently used nest sites after breeding ends.	2.2.1 Reliable identification of nesting habitat (improving habitat predictors) – UAV 2.2.2 Testing new technologies to improve habitat identification, classification, and mapping

h https://www.oregonmurrelet.org/.

Research question	Study objectives	Conceptual approach	Comments	Links to report sections
At what age and stage of structural development and spatial scale can murrelet nesting habitat become suitable, and does this change with stand condition at initiation?	1. Determine the age of forest when habitat is suitable by sampling a range of habitat types (based on region, dominant tree species, elevation, aspect, latitude, BEC zone, etc.). 2. Improve estimates of platform. development (limb size and epiphyte cover), especially in drier CDF and CWHxm units where moss is less common and litter and duff might provide nest substrates on large limbs.	Stand and tree level: Determine rates of recruitment of suitable nesting habitat as second-growth forest matures. Involves repeated measures at selected stands, including: • vegetation plots to record tree data; • measures of platform availability (ground surveys or LLAS, perhaps use of UAVs); • AV and ARU surveys to determine when murrelets start using the stands. Platform level: Determine the age at which trees start providing potential nest platforms. Involves: • re-analyzying data used by Burger et al. (2010) but applying regressions of dbh vs. tree age to obtain age estimates to replace the dbh used in that study; • expansion of the analysis by Sutherland, I.J. et al. (2016) to include a wider range of BEC zones and subzones/variants.	Most applicable to areas where suitable habitat is most reduced and recruitment is needed to meet recovery goals (East Vancouver Island and Southern Mainland Coast Conservation Regions). Stand and tree recruitment might require repeated sampling over 30+ years to obtain reliable longitudinal data, but the sampling will also have some short-term benefits. Sampling multiple stands in different stages of regeneration would provide short-term cross-sectional data. Could be linked to landscape-level study of effects of forest fragmentation and change. Could be linked to the Tree And Stand Simulator program (FLRNRORD, Forest Analysis Branch) to project tree development. Database for both types of analysis could be expanded with additional vegetation plots in under-sampled areas for better regional coverage. Sampling tied to forest inventory permanent plots.	2.2.3 Understanding recruitment of nesting habitat from regenerating forest
Can habitat suitability be maintained through low-basal-area-removal silviculture systems (adaptive management)?	1. Understand the effects of variable retention harvesting in order to maintain or recruit suitable habitat within the timber harvesting land base where harvesting has priority. 2. Understand the role of multiple potential nest trees in attracting breeding Marbled Murrelets. 3. Has some overlap with the next question, but is focussed more on enhancing habitat retention.	Involves: • use of radar to determine trends in numbers before and after treatments; • use of AV and ARU surveys to determine change in relative use by Marbled Murrelets and predators.	Some polygons already retain habitat suitability after selective logging (Haida Gwaii and elsewhere). Needs to be applied and tested on a larger scale. Needs a cost-benefit analysis to compare with alternative ways of maintaining habitat (e.g., dedicated unlogged WHAs among clearcuts).	2.2.3 Understanding recruitment of nesting habitat from regenerating forest

Research question	Study objectives	Conceptual approach	Comments	Links to report sections
Can harvest retention methods accelerate recruitment of stand-level habitat that has attributes of suitable murrelet nesting habitat in areas that have been depleted below recovery targets?	1. Determine potential for Marbled Murrelet nesting habitat recovery in areas where habitat is below recovery targets. 2. Provide silvicultural prescriptions for accelerating recruitment of habitat. 3. Identify the conditions in which Marbled Murrelets occupy maturing forests.	Might involve: • experimentally modifying maturing forest (e.g., thinning trees, inoculating canopy boughs with bryophytes, creating gaps in dense forests); • using associated measures of platform availability and their use by murrelets (AV or ARU); • compiling and evaluating recovered stands that are now suitable, and determining historical disturbance patterns that maintained habitat (e.g., drier Capital Regional District, Victoria, B.C., some telemetry nest stands in historic data).	Most applicable to areas where suitable habitat is most reduced and recruitment is needed to meet recovery goals (East Vancouver Island and Southern Mainland Coast Conservation Regions). Will require multi-year sampling to assess the effects of various treatments. D'Anjou et al. (2015) provide an example of adaptive habitat management for recruiting Spotted Owl habitat in British Columbia that includes options that also apply to Marbled Murrelet: thinning, creating gaps, and retaining veteran trees and trees with defects. In Oregon, a few murrelets are known to nest in younger trees (66 years old) that have mistletoe deformities (Nelson 1997).	2.2.3 Understanding recruitment of nesting habitat from regenerating forest
How will climate change affect the availability and quality of murrelet nesting habitat?	1. Determine the long-term effects of climate change, especially on the availability of mossy platforms and the most preferred tree species.	Involves repeated measures at selected stands, including: • vegetation plots for recording tree data; • measures of platform availability (as in previous project).	Could be linked with repeated AV and ARU surveys (see above research questions) and at-sea surveys in adjacent marine areas to understand both terrestrial and marine changes over time. Most applicable to the southern regions where climates are expected to change most. Likely to require repeated sampling over 30+ years to identify useful climate effects, but will also have some short-term benefits related to the research questions above (nest and patch fidelity). Tie to forest inventory permanent plots for long-term data collection.	2.3.1 Climate change influences on murrelet habitat availability and distribution

Research question	Study objectives	Conceptual approach	Comments	Links to report sections
Can vocal individuality be determined and used to test for site re-use and relative density?	1. Investigate nest site fidelity or stand fidelity. 2. Estimate the number of individual murrelets likely to be breeding at the stand scale (ARU sampling area). 3. Describe patterns of behaviour by individuals (daily, seasonal). 4. Investigate social interactions and patterns of activity by "non-resident" individuals. 5. Improve understanding of the social function (spacing behaviour?) of murrelet vocalizations over forest habitat.	Deploy ARUs at active stands to collect a data set for analysis (can use existing recordings from ARU project for pilot study). • Collect measurements of call elements for calling bouts to build a vocal "fingerprint." • Compare "fingerprints" against each other using statistical methods to estimate the number of individuals per recording and between recordings.	Dechesne (1998) showed that individual murrelets might be distinguished based on spectrograms of their vocalizations, but this has not been developed as a censusing or monitoring tool. Currently, comparing spectrograms is very laborious because this analysis cannot be automated using current tools and has to be done manually. This approach could begin with a proof-of-concept/pilot to identify individuals in a subset of recordings from ARUs.	2.2.2 Testing new technologies to improve habitat identification, classification, and mapping

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APPENDIX 1 Initialisms/acronyms and their definitions

API	air photo interpretation
ARU	autonomous acoustic recording unit
AV	audio-visual
B.C.	British Columbia
BEC	Biogeoclimatic Ecosystem Classification
CDF	Coastal Douglas-fir
CWH	Coastal Western Hemlock
CWHvm	Coastal Western Hemlock very wet maritime subzone
CWHxm	Coastal Western Hemlock very dry maritime subzone
dbh	diameter at breast height
FLNRORD	B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development
GPS	global positioning system
LiDAR	light detection and ranging
LLAS	low-level aerial survey
PTTs	satellite platform terminal transmitters
SFU	Simon Fraser University
UAVs	unmanned aerial vehicles
UVIC	University of Victoria
VHF radio telemetry	very high frequency radio telemetry
VRI	Vegetation Resource Inventory
WHAs	Wildlife Habitat Areas