Appendix C: Background Reports/Supporting Documents

Attachment C-1. Washington Department of Natural Resources and U.S. Fish and Wildlife Service. 2015. Potential impacts and mitigation focus paper: potential impacts and mitigation. Wash. Dep. Nat. Resour., Olympia. 26 p.

Attachment C-2. Peery, M. Z., and G. M. Jones. 2018. Using population viability analyses to assess the potential effects of Washington DNR forest management alternatives on marbled murrelets. Univ. Wisconsin, Madison. 74 p.

Attachment C-3. Washington Department of Natural Resources and U.S. Fish and Wildlife Service. 2015. P-stage focus paper: estimating the location and quality of marbled murrelet habitat. Wash. Dep. Nat. Resour., Olympia. 16 p.

Attachment C-4. Washington Department of Natural Resources and U.S. Fish and Wildlife Service. 2015. Long-term forest cover focus paper: areas of long-term forest cover. Wash. Dep. Nat. Resour., Olympia. 9 p.

Potential Impacts and Mitigation Focus Paper

Potential Impacts and Mitigation

Focus Paper #5

This focus paper was part of a series presented to the Board of Natural Resources in October and November 2015 to inform development of the marbled murrelet long-term conservation strategy alternatives. The purpose of this paper is to describe how possible impacts to murrelet habitat from harvesting, edge effects and disturbance activities on DNR-managed lands are assessed and mitigated across conservation alternatives.

■ Introduction

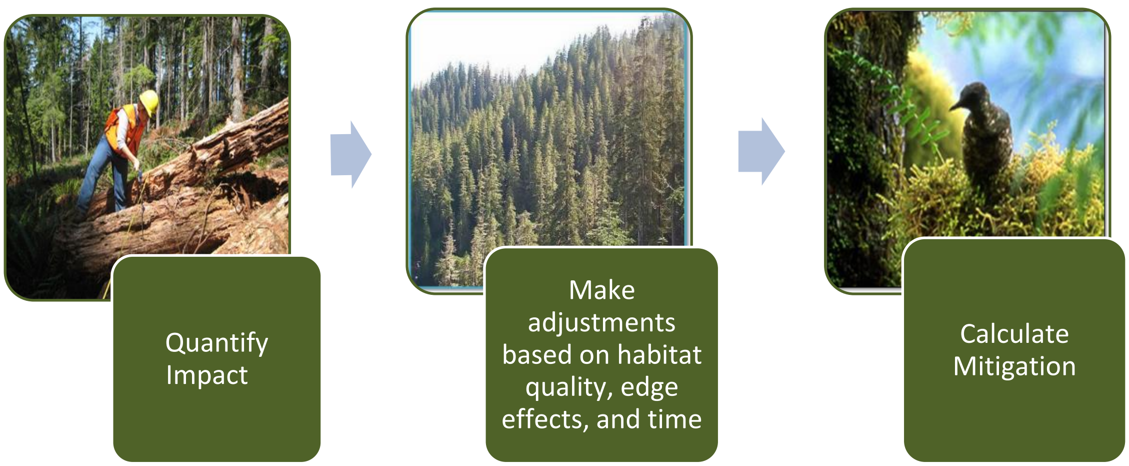
The analytical framework (Refer to Appendix B, "Analytical Framework Focus Paper") identifies three sources of possible impacts to marbled murrelets that may incidentally occur on state-managed lands: harvest-related impacts, edge-influenced impacts and disturbance-related impacts. These impacts can be quantified using repeatable, objective methods based on sound science. By doing so, these impacts can be evaluated against the minimization and mitigation proposed under each alternative being developed for the long-term marbled murrelet conservation strategy.[1]

[1] As defined in the 1997 HCP, mitigation "includes methods to reduce adverse impacts of a project by (1) limiting the degree or magnitude of the action and its implementation; (2) rectifying the impact by repairing, rehabilititating, or restoring the affected environment; (3) reducing or eliminating the impact over time by preservation and maintenance operations during the life of the action, or; (4) compensating for the impact by replacing or providing substitute resources or environments."

■ Quantifying Impacts and Mitigation

Quantifying impacts to marbled murrelet habitat and determining mitigation hinges upon identifying and assigning value to habitat. The value of habitat is related to its likelihood of use by murrelets, and generally increases with age and structural complexity of the forest.[2] Because not every acre of habitat is of equal value to the murrelet, it is important that the varying weights of impact or mitigation provided by each acre are quantified appropriately.

Figure 1. Conceptual Steps in Quantifying Impacts and Mitigation



■ Harvest Impacts and Mitigation

Harvest impacts include activities such as timber harvest or road building that result in the removal of marbled murrelet habitat (acres with P-stage values). These activities primarily occur in the managed forest, outside areas of long-term forest cover (LTFC) (refer to Appendix G, "LTFC Focus Paper"). Removing habitat can result in the loss of existing nests and reduce future reproductive capability, therefore impacting the species. The analytical framework provides a methodology to assess harvest impacts to potential marbled murrelet habitat over the life of the *State Trust Lands Habitat Conservation Plan* (1997 HCP).

For analysis purposes, the framework assumes that the loss of habitat from harvest in the managed forest over time will be offset by habitat gains that occur in areas protected by the conservation strategy. Each habitat acre harvested and each acre grown have different habitat *values*, depending on their P-stage value, their location relative to forest edges, distance from other habitat areas, and in which decade they are harvested or develop into habitat.

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[2] Refer to Appendix E, "P-stage Focus Paper."

The equation in Table 1 is simplified. Calculating the value of the habitat is a more complex process that includes the P-stage value plus other factors influencing a forest stand's value as murrelet habitat. These factors include whether the acres are in an edge condition, where they are located on the landscape, when the harvest and/or new habitat development occurs, and whether the habitat is subject to disturbance. These factors are discussed in detail in the next section.

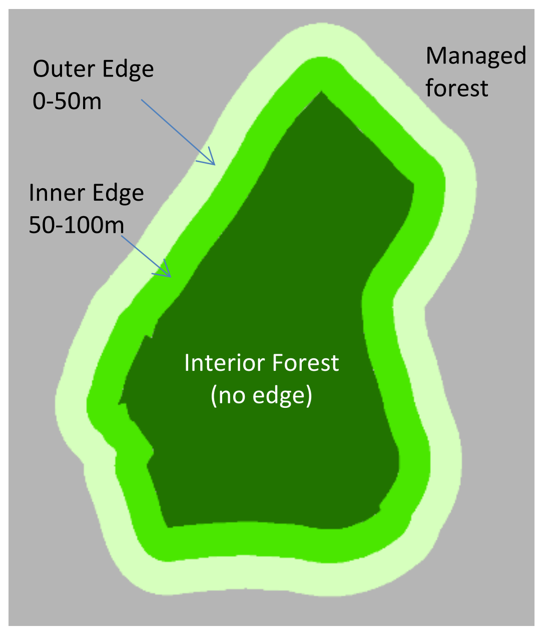
Table 1. Simplified Calculation of Harvest Impacts and Mitigation

Acres Harvested		Habitat Value		Mitigation Acres Needed
500	X	.36	=	180

Edge Impacts

A forest edge is an abrupt transition between two populations of trees, where the characteristics of the forest on one side are different from the other. Some edges are naturally occurring, created by wetlands, streams, or avalanche chutes, and others are created through human activity. Timber harvesting can create a high contrast edge along the boundary between the harvested area and the adjacent forested stands. Exposed harvest edges alter microclimate effects (light, moisture, wind, and temperature gradients) in adjacent stands for distances of up to 240 meters (787 feet) (Chen and others 1993, p. 291, 1995, p. 74). For this analysis we use a distance of 100 meters (328 ft.) to account for the most significant physical and biological effects to murrelet habitat along harvest boundaries due to the loss of trees to windthrow, loss of moss for nesting substrate, reduced canopy cover, altered forest composition, and increased risk of nest predation (Chen and others 1992, pp. 390-391, van Rooyenand others 2011, p. 549, Raphael and others 2002, Malt and Lank 2009, p. 1274). For purposes of analyzing edge effects, we distinguish between an outer edge (the first 50 meters from an edge) and inner edge (50-100 meters from an edge). Refer to Figure 2.

Figure 2. Illustration of Forest Edges



How do Edges Impact Murrelet Habitat?

Timber harvest edges can influence adjacent murrelet habitat in two ways: through increased risk of nest predation and habitat degradation resulting from windthrow and microclimate changes.

Edge effects resulting from timber harvest may increase the risk of marbled murrelet nest predation in habitat located close to unnatural edges (harvest edges and major road corridors). A review of known murrelet nests found average nest success was 38 percent within 50 meters (164 feet) of a forest edge, and 55 percent at distances greater than 50 meters from an edge. Most nests failed because of predation (60 percent), and predation was higher within 50 meters of an edge than within the forest interior. No murrelet nests greater than 150 meters (492 feet) from an edge failed because of predation (Manley and Nelson 1999, McShane and others 2004, p. 4-89). Based on these data from actual murrelet nests, the average nesting success rate within 50 meters of an unnatural edge is 69 percent of nests located greater than 50 meters from an edge.

Predator populations are in highest abundance along forest edges bordered by newly initiated stands.

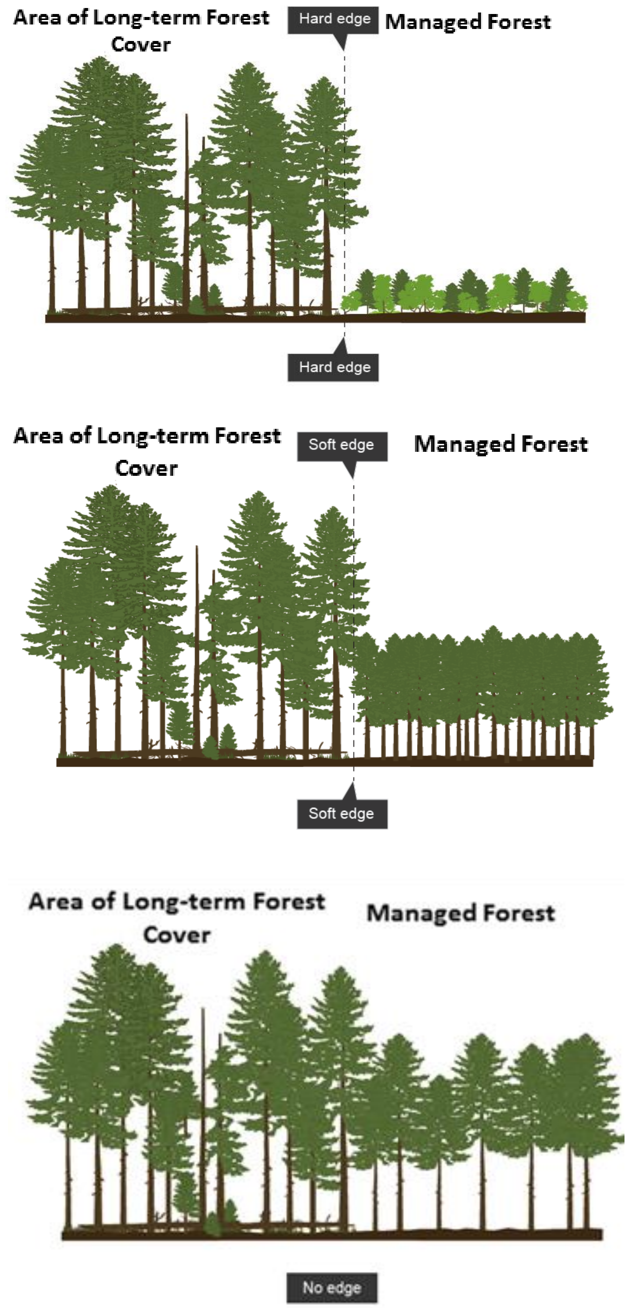
Observations at known nests are affirmed in other research studies that examined the fate of simulated murrelet nests relative to forest edges and stand structure (Raphael and others 2002, Malt and Lank 2009). Simulated murrelet nests located within 50 meters (164 feet) of high contrast edges created by recent timber harvest are 2.5 times more likely to be disturbed by predators relative to nests located in adjacent interior forest (Malt and Lank 2009, p. 1274). The increased predation risk is associated primarily with Steller's jays (*Cyanocitta stelleri*) because they are habitat generalists that respond positively to forest fragmentation and preferentially use forest edges due to the abundance of berries and insects in young regenerating forests (Malt and Lank 2009, pp. 1283-1284). Predation risk associated with harvest edges declines over time (20 to 40 years after timber harvest) as young forests regenerate and become dense, simple-structured stands with no understory (Malt and Lank 2009, p. 1282).

Edge effects also increase windthrow and alter microclimate regimes, both of which impact murrelet habitat. Van Rooyen and others (2011) analyzed platform abundance, epiphyte growth, and microclimate at forest edges to understand edge effects on murrelet habitat. In "outer edge forest," which the authors define as 0 to 50 meters from an edge, they found platform abundance adjacent to regenerating forest (a "hard edge," approximately 0 to 20 years old) was reduced by 75% in comparison with interior forest. Platform abundance at "soft edges" (young forest stands approximately 21 to 40 years old) was only 60 percent of the abundance found in interior forests.[3] Reductions in platform abundance at these various-aged edges were attributed to the loss of

[3] Table 4 in van Rooyen and others 2011; authors found a mean of 16.02 ± 5.14 platform trees at soft edges, as opposed to 26.8 ± 6.60 platform trees in interior forests (16.02 divided by 26.8 equals 60%).

platform-bearing trees from windthrow and other mortality sources, and to microclimatic effects that diminished epiphytic growth important to development of potential nesting platforms. The lesser effects at soft edges suggests that epiphyte growth is recovering from the hard edge impacts and is contributing more towards platform development.

Figure 3. Edges Change with Forest Succession



How far Into the Forest do the Edge Effects Occur?

The extent of influence regarding microclimate and epiphyte effects into stand interiors has not been well studied, but evidence from a study in western Washington and Oregon old-growth forests that looked at 0, 30, 60, 120, 180, and 240 meters suggests appreciable tree mortality decreased substantially beyond 120 meters from edges (Chen and others 1992). Edge effects diminish with increasing distance from a hard edge. We selected 100 meters to represent the suite of edge effects (predation, habitat degradation, and windthrow). Recognizing that effects diminish with distance from the edge, we assumed that "inner edge" effects are half relative to those in the outer edge.

How Does Forest Succession Influence Edge Effects?

Studies have shown that forest edge effects diminish over time, as harvest areas regenerate and develop into mature forest stands (Matlack 1993, Harper and others 2005, cited in Van Rooyen 2012; refer to Figure 3). Early stages of stand development following harvest, referred to as *ecosystem initiation*, are characterized by actively growing young trees and other herbaceous vegetation (DNR 2007). With their rapidly growing vegetation and increasing forage base (for example, insects, berries), ecosystem initiation stands provide a wide range of food sources and more opportunities for foraging to predators, particularly Steller's jays, a known predator of marbled murrelets (McShane and others, 2004).

Over time, the vegetation in the ecosystem initiation stand fills the available growing space and the stand develops into a *competitive exclusion* stage, characterized by more than 70 percent canopy cover and simpler stand structure. Stands in these stages have the lowest biodiversity and the least favorable conditions for wildlife when compared to all the stand development stages (DNR 2007). In competitive exclusion, fewer microhabitats for foraging are available for the predators (McShane and others 2004). As predation decreases, however, microclimate effects and windthrow continue to impact adjacent habitat by allowing sunlight and wind into the adjacent marbled murrelet habitat. We estimate that once stands on DNR-managed lands reach a height of 40 feet, they have reached the beginning stages of competitive exclusion.

When adjacent forests reach 80 feet in height they are assumed to ameliorate edge effects, for the purposes of this analysis (Malt and Lank 2009, Van Rooyenand others 2011). Once stands achieves this height, the crowns begin to overlap with those of the stand containing murrelet habitat, diminishing the impacts resulting from altered climatic regimes and windthrow.

How Does the Analytical Framework Address Edge Effects?

The analytical framework adjusts the mitigation value of habitat located in the edges of long-term forest cover to account for the edge effects that will impact that habitat over the life of the 1997 HCP. The adjustment factors are based on proximity to habitat (inner or outer edge) and edge condition (hard, soft, or no edge).

> Both edge location (inner or outer) and edge condition (hard, soft, or no-edge) play a role in determining edge effects.

The analytical framework categorizes edge conditions into three groups: hard, soft, and no edge. Newly initiated stands adjacent to the mature forest containing murrelet habitat are considered to create "hard edge" where their height is 40 feet or less (refer to Figure 3 and Figure 4). Stands in competitive exclusion adjacent to a mature forest containing murrelet habitat are considered to create "soft edge" where their height is between 40 and 80 feet. Finally, stands with a height greater than 80 feet adjacent to a mature forest containing habitat are not considered to be "edge-creating;" as they have a diminished effect on the adjacent habitat compared to hard edges

Edge conditions are not static over time; they change as forests regenerate. The relative percentages of edge across DNR-managed lands will, however, remain generally similar throughout the life of the 1997 HCP. This is because DNR will continue to manage its forest consistent with its policies, continuing the pattern of sustainable harvest in portions of the analysis area while leaving the LTFC portion to develop mostly without direct management intervention.

Figure 4. Example of Hard Forest Edge Created by Harvest

How are Edge Effects Quantified?

There are two adjustment factors are used in the analytical framework to address edge effects – one that is applied to outer edge and another applied to inner edge. When applied, these factors adjust the value of habitat *down*, reflecting the edge effect.

First, discounts are applied to habitat in a particular edge condition based on the scientific information about how that condition impacts murrelet nest success. No discounts are assumed for interior forests (forests in a "no-edge" condition).

For forests in the outer edge (Table 2), these impacts are:

- Hard, outer edges: predation, microclimate, and windthrow;
- Soft, outer edges: microclimate only.

Table 2. Outer Edge Effect

Forest Inventory Data-Derived Edge Condition[a]			Discount Multiplier		Outer Edge Factor
Hard	21%	x	.83[b]	=	.174
Soft	33%	x	.40[c]	=	.132
No-Edge	46%	x	0 [d]	=	0
			Sum	=	**.31**

[a] Percentages are presented here and in Table 3 as examples. Each alternative conservation proposal will have different percentages, due to differences in the amount and configuration of LTFC.

[b] Van Rooyen and others (2011) found that platform tree density at hard edges is 25 percent of the density found in interior forests. McShane and others (2004) summarized from different sources that nests at hard edges are 69 percent as successful as nests in interior forests. When combined (.25 x .69 = .17), an 83% discount results for this edge condition.

[c] Microclimate conditions in soft, outer edges result in only 60 percent of the platform density relative to interior forests (Van Rooyen and others 2011). Therefore, a 40 percent discount is applied.

[d] No edge discounts are assumed.

For forests in the inner edge (Table 3), only microclimate impacts (not predation), are considered, as follows:

- Hard, inner edges: microclimate (not predation)
- Soft, inner edges: microclimate, but at half the intensity as a hard edge.

Table 3. Inner Edge Effect

Forest Inventory Data-Derived Edge Condition			Discount Multiplier		Inner Edge Factor
Hard	21%	x	.415[a]	=	.09
Soft	33%	x	.20[b]	=	.07
No-Edge	46%	x	0[c]	=	0
			Sum	=	**.15**

[a] Only microclimate, not a combination of predation and microclimate, is assumed to be a factor in inner, hard edges. So half of the discount applied to outer edges (.83/2).

[b] Microclimate conditions in soft, inner edges are assumed to be half of those in outer edges (.40/2).

[c] No edge discounts are assumed.

The resulting edge factors are then multiplied against the number of P-stage acres in each edge condition to derive the total potential take from edge effects. Because each alternative being developed for the long-term conservation strategy has a different amount of long-term forest cover, and in different configuration on the landscape, the resulting calculations and edge factors differ slightly across the alternatives.

■ Disturbance Impacts

In addition to harvest and edge impacts, forest management activities can impact murrelets by creating unfamiliar sights and sounds that may disturb them. This can be disruptive to murrelets during their nesting season when they are incubating eggs and caring for their young. The analytical framework refers to impacts that result from activities that create these audio and visual stimuli as *disturbance impacts*. Quantifying disturbance impacts requires a different approach, because unlike harvest or edge impacts, the vegetation within habitat is not altered through removal or degradation. Instead the environments within habitat are temporarily altered, with the impact of possibly interrupting the murrelet nesting behavior. In addition, some activities occur repeatedly during the nesting period. To quantify potential disturbance impacts, the analytical framework estimates the magnitude and frequency of all activities with the potential to disturb murrelets during the nesting season.

What are Disturbance Impacts?

A disturbance event is considered significant when an activity causes a murrelet to delay or avoid nest establishment, flush away from an active nest site, or abort a feeding attempt during incubation or brooding of nestlings. A flush from a nest site includes movement out of an actual nest, off of the nest branch, and away from a branch of a tree within suitable habitat during the nesting season. Such events are considered significant because they have the potential to result in reduced reproduction, hatching success, fitness, or survival of juveniles and adults (USFWS 2012).

What Activities can Disturb Murrelets?

When evaluating the potential for audio-visual disturbance of nesting murrelets, DNR and USFWS grouped activities into three categories:1) aircraft, 2) ground-based activities, and 3) impulsive noise-generating activities such as blasting and pile-driving. Aircraft activities includes any forest management activity that requires the use of low-flying, small fixed-wing planes and small helicopters, such as aerial spraying of herbicide treatments. Examples of ground-based activities include timber harvest and hazard tree removal, and road and trail maintenance. Activities generating impulsive noise include blasting to generate rock for forest roads.

How are Disturbance Events Evaluated?

It is very difficult to separately analyze an animal's response to either auditory or visual stimuli alone (Pater and others 2009), and most studies have not been designed to adequately control for those factors separately. As such we evaluate both the audio and visual component of potentially disturbing activities together.

The body of knowledge on bird response to disturbance indicates that human activity can potentially impact nesting success and can be energetically costly to individual birds. Disturbance can have effects throughout the nesting season, including the nest establishment, incubation, and chick rearing phases. Marbled murrelet response to disturbance is variable and appears related to the developmental stage of the individual bird exposed to stimuli, degree of habituation existing prior to exposure, and whether there is a visual component to the stimuli. Murrelets have responded behaviorally to disturbance in ways that create a reasonable likelihood of injury to the adult, the chick, or both.

How far From Murrelet Habitat can Activities Disturb Murrelets?

In a review of best available information on avian ecology, disturbance, and acoustics, USFWS determined that significant disturbances to murrelets can occur within a distance of 100 meters of suitable habitat throughout the murrelet nesting season (USFWS 2012a). Exceptions include blasting, (0.25 mile-radius disturbance distance), and large aircraft (for example, military jets) where the disturbance distance is defined by where the sound exposure level (SEL) from the aircraft meets or exceeds 92 dBA (A-weighted decibels).

What Time of Year can Murrelets be Disturbed?

The USFWS has previously determined that murrelets can be disturbed during their nesting season, which occurs between April 1st and September 23rd, 176 days out of the year. There is enough overlap in nest establishment, incubation and nestling periods to assume there is equal risk of murrelet exposure to disturbances occurring throughout the nesting season (USFWS 2012b).

How do Murrelets Respond to These Disturbances?

Murrelet responses are expected to vary according to the type of activity in combination with the timing, duration, and frequency of the exposure. Many forest dwelling birds (including raptors, golden eagles, and Mexican spotted owls) exhibit increased flush rates due to noise. Chicks and adults are expected to vary in their response. Observations by murrelet researchers in the field indicate that murrelet chicks may not have a noticeable response to noise and visual stimulant all, or may respond by becoming very still, lying flat on the branch (Hebert and others 2006). As such, murrelet chicks are not expected to prematurely leave a nest in response to these types of noise and visual stimuli. However, adult murrelets may abandon or delay nest establishment, or abort or delay feedings in response to exposure to these stimuli. Adults that are incubating an egg are not expected to flush (USFWS 2012a).

How Does the Analytical Framework Evaluate the Significance of Each Activity?

The 1997 HCP permits a range of forest management activities. The analytical framework relies upon an analysis of all activities permitted to occur on DNR-managed lands to determine whether they have the potential to cause disturbance to marbled murrelets. The framework identifies 36 activities that may cause disturbance. Examples include:

> Disturbance is quantified by determining the the birds' likely response given the duration and intensity of a stressor and converting that information into acres impacted.

- Recreational site use
- Sand and gravel sales
- Electronic site maintenance
- Road use and maintenance
- Collection of western greens, Christmas greens, and mushrooms.

In order to quantify the potential impacts that result from these activities, the analytical framework assigns values for the following qualities that are used to measure the significance of the disturbance activities: stressors, duration, and response. Disturbance is quantified by determining the birds' likely response given the duration and intensity of a stressor and converting that information into acres of habitat exposed.

Stressors are physical, chemical, or biotic phenomenon or a circumstance that constitutes a real or perceived challenge or threat to an organism's physical health, homeostasis, or homeostatic mechanisms. Stressors include:

- Ground-based noise (examples: chainsaws that are harvesting trees, removing hazard trees from campgrounds, or heavy equipment maintaining roads);
- Visual disturbance (example: human presence around nest trees, such as someone hiking around or near a nest tree);
- Human activity that attracts predators (example: campgrounds close to murrelet habitat, because the human activity draws the predators to the habitat);
- Impulsive noise (example: blasting in rock pits to generate crushed rock for forest roads)
- Aircraft noise (example: sounds generated by helicopters and small planes).

Duration represents the length of time an activity is present within close proximity of murrelet habitat. Duration measures how long the habitat would it be exposed to that activity. Duration categories include:

- <1 day
- <7 days
- >7 days and < 30 days
- >30 days

Response represents the murrelet's possible behavioral reaction to various auditory and/or visual disturbances. Responses include:

- No significant response
- Aborted feedings
- Adults flushing
- Mortality or loss of productivity from removal of nest tree
- Mortality from predation
- Hearing damage

How Does the Analytical Framework Evaluate Disturbance?

Once each activity is assigned stressor, duration and response the activities are allocated into six groups based on similar combinations of these three categories (refer to Table 4). For each group, the analytical framework estimates the total habitat area within the appropriate distance bands of each activity (100 meters of each ground-based and small aircraft activity and ¼ mile for blasting) and then adjusts the acreage for habitat quality, time of year that the activity occurs, and then by the total years remaining in the 1997 HCP.

Table 4. Activity Groups by Stressor, Distance, Duration, and Response

Group Assignment	Stressor	Disruption Distance	Duration	Response/Impact

Group 1 (includes green collecting, precommercial thinning, non-motorized trail use, minor road maintenance)	Ground-based Noise and Visual Disturbance	≤100 m	< 1 Day	No significant response based on duration; minimal to no impacts
Group 2 (includes firewood collection, road reconstruction, major road and trail maintenance, communications facilities)	Ground-based Noise and Visual Disturbance	≤100 m	< 7 Day	Aborted feedings, Adults flushing; potential harassment[1]
Group 3 (campground use and maintenance)	Ground-based Noise and Visual Disturbance Predator Attraction	≤100 m	< 1 Month	Increased predation risk, Aborted feedings, Adults flushing; potential harm[2]
Group 4 (includes timber harvest, motorized trail use, new road and bridge construction)	Ground-based Noise and Visual Disturbance	≤100 m	>7 Days < 1 Month	Aborted feedings, Adults flushing; potential harassment
Group 5 (sand and gravel extraction, blasting)	Ground-based Noise and Visual Disturbance	≤.25 mi	>7 Days < 1 Month	Hearing damage from blast noise (within 100m), Aborted feedings, Adults flushing; potential harm or harassment
Group 6 (aerial herbicide application)	Aircraft Noise	≤100 m	< 7 Days	Aborted feedings, Adults flushing; potential harassment

[1]Harass is defined as an act which creates the likelihood of injury to wildlife by annoying it to such an extent as to significantly impair normal behaviors, including breeding, feeding, or sheltering (50 CFR 17.3).

[2]Harm is defined as act which actually kills or injures wildlife, and can include habitat modification that significantly impairs essential behaviors such as breeding, feeding, or sheltering (50 CFR 17.3)

When estimating possible responses of the marbled murrelet to human activity, it is important to note that empirical data are lacking for the range of activities represented in Table 4. Studies evaluating the effects of noise on various animals frequently use different metrics, and often fail to report which metrics they use, making comparisons and interpretation difficult. For the purposes of this analysis, we do not expect that short-term exposures to low intensity stimuli that last less than 1 day will adversely affect marbled murrelets. However, any reduction in feedings has the potential to physiologically effect a murrelet chick, depending on how many feedings are received in one day, and presumably, the energy content of the food that is delivered. Further, aborted or delayed feedings have the potential to increase energy demands and predation risk on adult murrelets. Conversely, when weighing these risks, we must also consider that many of these short duration activities are intermittent and low intensity (e.g. mushroom pickers walking through a stand of suitable habitat) and pose little risk. After considering these factors, we expect that exposure of juvenile and adult murrelets to these low-intensity activities, when lasting <1 day are not expected to result in measureable effects, and are therefore insignificant.

Adjusting Disturbance Impacts for Habitat Area, Quality, and Time

Using DNR's GIS and other data, including annual activity reports and summaries, the analytical framework identifies the *footprint* of each activity within each group, as it occurs on DNR-managed lands within the range of the murrelet. Using a distance buffer with a width equivalent to the area of disturbance around the footprint, the framework sums the total area of P-stage habitat for each activity. These totals are then summed for each group.

The analytical framework only quantifies disturbance for the habitat located within LTFC. This is because we assume that habitat located outside of LTFC will be removed over time, therefore the expected disturbance impacts in managed areas are accounted for in the harvest impact estimates. The P-stage acreage is multiplied by the proportion of DNR-managed lands within LTFC to reflect the habitat acres disturbed within LTFC by each group.

As with edge effects, the effects of disturbance vary based on the *quality* of habitat (P-stage value). Therefore, in evaluating disturbance take, acres of disturbed habitat are multiplied by their P-stage value. (Refer to Attachment 1 for an example of how this works.)

The magnitude of disturbance impacts are also influenced timing; by *when* they occur in a particular year and *how often* throughout the year. This is because activities that disturb marbled murrelets impact their reproductive activities, such as nest incubation, caring for young, which only occur during the nesting season. This analysis is limited to the time period of the murrelet nesting season, when impacts to reproduction are most likely to result.

Timing is considered in two dimensions: the time of year (i.e., marbled murrelet nesting season or not; and if so, how many days) and the duration of the activity during the week (i.e., occasional versus everyday occurrence, or a 5-day workweek occurrence).

To factor time adjustments into the estimate of disturbance impact, the framework multiplies the weighted habitat acres in LTFC by the number of days the activities within each group overlaps with the nesting season. The number of days the activities overlap with the nesting season is influenced by how often an activity occurs during the week. For example, road maintenance on DNR lands is expected to only occur 5 days a week, whereas campground use may occur on weekdays or weekends throughout the summer. The result is an adjusted number of acres potentially affected by disturbance activities during the nesting season.

Some of these habitat acres will be disturbed repeatedly over the life of the 1997 HCP. To account for this, the framework takes the time-adjusted weighted habitat acres and multiplies them by the years remaining in the 1997 HCP (52 years), for a final amount of statewide time-adjusted acres of P-stage habitat in LTFC disturbed during the nesting season. This final acreage calculation is an estimate of DNR's potential disturbance impact. An example of how these adjustments work is provided as Attachment 1.

■ Where Will Mitigation Occur?

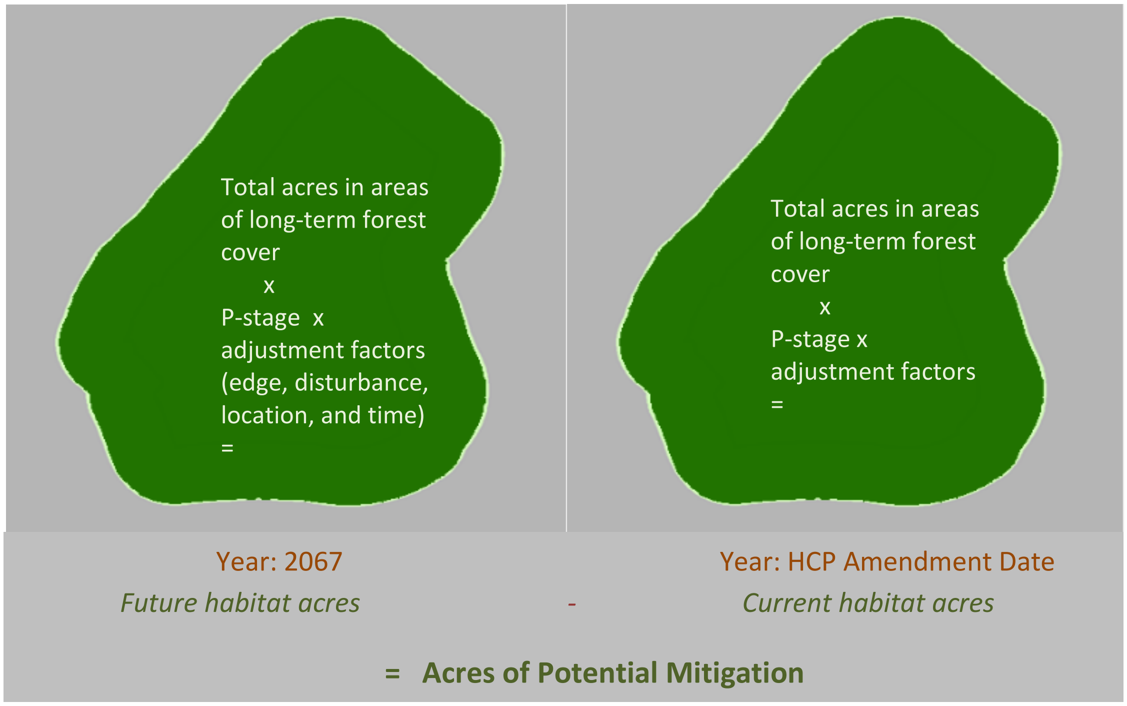
DNR's conservation strategy uses areas of long-term forest cover (LTFC) to provide both minimization and mitigation for the types of impacts described previously.[4] Areas of LTFC are established to meet a variety of conservation objectives, but within the murrelet conservation strategy they serve three major purposes:

- To conserve most marbled murrelet habitat on DNR-managed forest lands;
- To minimize overall impacts to that habitat and increase its quality by including additional contiguous area to increase the area of interior forest habitat;
- To mitigate impacts from activities in the managed forest by allowing new and higher quality murrelet habitat to develop through time.

Similar to how impacts are adjusted for edge conditions and other factors, adjustments must be made to the mitigation value of habitat grown over the life of the 1997 HCP. Mitigation provided by LTFC can be expressed as the number of acres of marbled murrelet habitat grown within those areas through the end of the 1997 HCP. Mitigation value is determined by subtracting "current habitat acres" from "future habitat acres." Refer to Figure 5. The total acres of P-stage habitat located inside and out of areas of long-term forest cover varies across conservation alternatives, depending on what is included LTFC (size of the conservation areas, occupied site buffer widths, and other landscape components). For each alternative, this habitat can be quantified. Total "raw" acres of habitat with P-stage values are estimated using DNR's inventory information of forest lands. The total "raw" acres within each P-stage category (.25, .36, .47, .62, .89, 1.0) are then multiplied by their respective values. These raw acres are converted to "weighted habitat acres," which incorporates habitat quantity and quality, including edge effects, into one unit. All of the totals are summed, producing the total "current habitat" for each alternative.

[4] Refer to Appendix G, "Long-term Forest Cover Focus Paper."

Figure 5. Calculating Mitigation in Areas of Long-Term Forest Cover



When the acres of habitat are multiplied by their respective P-stage value and other adjustment factors, the total acres in that category that can be used as mitigation is reduced, according to quality. For example, if 100,000 acres of LTFC only has a P-stage value 0.25, this is valued as 25,000 acres for purposes of calculating mitigation.

Not all Habitat is Considered for Mitigation

An *interim strategy* for marbled murrelet conservation has been operating since the 1997 HCP was adopted. This strategy included protections for occupied sites and reclassified habitat (refer to Appendix D, "Occupied Sites Focus Paper," for a brief description of the interim strategy). USFWS issued an incidental take permit for impacts to the murrelet occurring on DNR's managed forest lands over this time period, and DNR has complied with that permit. Habitat has also been growing and developing for the murrelet during this time. However, no mitigation credit will be given for that interim habitat development because this analysis starts with current conditions. The analytical framework is forward-looking. It begins in "Decade 0" (current year until 2025) and focuses on potential impacts and mitigation occurring out to 2067 ("Decade 5"). Habitat is expected to increase within areas of long-term forest cover through that time period.

In addition, the analytical framework does not give credit to forest stands within LTFC that do *not* have a P-stage value; stands that are too young to count toward total acres of habitat. These stands may still have conservation value for the murrelet by reducing fragmentation.

Adjusting Mitigation Values for Time

Adjustments to the mitigation value of habitat are necessary to accommodate edge and disturbance effects, as described previously. However, a different kind of adjustment is needed to address another modifier of habitat quality: time. Habitat that exists today currently provides nesting opportunities to murrelets and is therefore more valuable than habitat that will be developed further into the future (as forests mature). If an impact to that habitat happens today, the offsetting mitigation (the same value of habitat becoming available to the murrelet) may not happen for several years. The analytical framework takes this into account by adjusting the value of mitigation through time, which is expressed by decade to the end of the 1997 HCP.

The decadal adjustment factor is based on how much habitat develops in a particular decade, as well as which decade that habitat is realized. For example, the total habitat that develops in long-term forest cover from the present into the first decade receives full mitigation credit to offset harvest in the managed forest within that first decade; all of the acres are counted. However, the total habitat that develops between the first and second decades receive only 80% of the total credit. This is because the habitat that grows during this decade will contribute to murrelet conservation for less time, four out of the five total decades (4/5 = 80%). Growth occurring between the second and third decades receives 60% credit (three out of five decades of growth), and so forth through to the end of the 1997 HCP. (Refer to Table 6)

Table 6. Adjusting Future Habitat in Mitigation Value. Numbers are for illustration purposes only. They are not a representation of DNR-managed lands.

Decades	Habitat Acres	Difference Between Decades	Decade Adjustment Factor	Acres of Mitigation Credit
0	1000			
1	2000	1000	1.00	1000
2	3000	1000	0.80	800
3	4000	1000	0.60	600
4	5000	1000	0.40	400
5	6000	1000	0.20	200
			Total Mitigation Credit:	**3000**

Adjusting Mitigation Values Based on Location

Across the analysis area, some landscapes are less valuable, or "marginal" for long-term marbled murrelet conservation due to a lack of suitable habitat, isolation from known occupied sites, and low-capability for developing future habitat based on forest types. An example of a marginal landscape for marbled murrelets is the Capitol Forest, located in the South Puget Planning Unit. The Capitol Forest is a large landscape that encompasses more than 95,000 acres of DNR-managed lands, but currently contains relatively little murrelet nesting habitat (< 2,000 acres). DNR conducted marbled murrelet surveys at more than 450 survey stations located within the Capitol Forest. Murrelet presence was detected at only one survey station, and no murrelet occupancy behaviors were detected during any of the surveys. The Capitol Forest has been intensively managed for timber production for many decades, and is comprised of forest dominated by second-growth Douglas-fir plantations which have a low capability to develop into murrelet habitat during the life of the 1997 HCP. Due to the limited and fragmented nature of potential nesting habitat in this landscape, and no known occupied murrelet sites, we consider the Capitol Forest to be a marginal landscape for murrelet conservation.

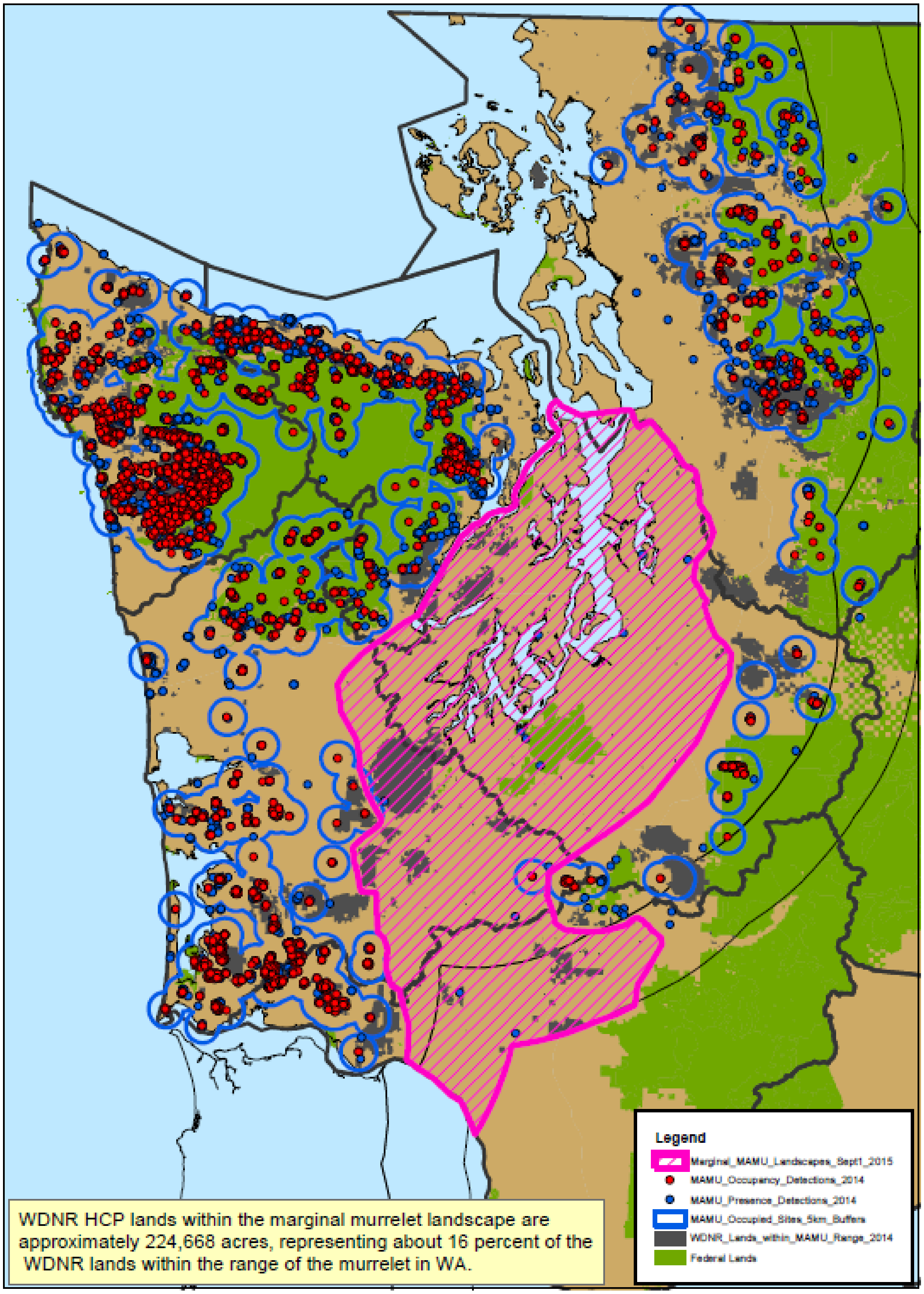
To define marginal murrelet landscapes we considered multiple factors:

- proximity to known occupied sites (within a distance of 5 km from known occupied sites[5]),
- results of marbled murrelet survey information,
- proximity to murrelet critical habitat on federal lands,
- current habitat distribution, and
- capability for developing future habitat.

Our delineation of marginal murrelet landscapes includes more than 224,000 acres of DNR-managed lands located primarily in the Puget Trough lowlands from the Kitsap Peninsula south to the Columbia River (refer to Figure 6). These landscapes currently contain low amounts of murrelet habitat (about two percent) in small scattered patches, are located further than 5 km from any known occupied murrelet sites, and have a relatively low capacity for developing future habitat within the life of the 1997 HCP.

[5] The 5 km proximity distance is derived from research in southern Oregon and northern California that found that murrelets are less likely to occupy habitat if it is isolated (> 5 km) from other nesting murrelets (Meyer and others 2002).

Figure 6. Map of Marginal Landscapes for Murrelet Conservation



Calculating Take and Mitigation in Marginal Landscapes

In the marginal murrelet landscapes, we reduce all P-stage habitat values by 75 percent. In other words, P-stage habitat acres are given 25 percent of the P-stage habitat value for the purposes of calculating take and mitigation. In this way, we still account for potential take of murrelets associated with any habitat loss that may occur in these landscapes. We think the potential for take of murrelets in these areas is very low, but recognize that murrelet occupancy in these areas is not entirely discountable because they are located within the range of the species in Washington. Likewise, we apply mitigation credit for habitat conserved in areas of long-term forest cover, but at a reduced rate relative to other areas within the DNR-managed lands that are more likely to contribute to long-term murrelet conservation.

■ Putting it all Together: Take and Mitigation

Calculating the extent and intensity of potential impacts through the life of the 1997 HCP, and ensuring that a long-term conservation strategy minimizes and mitigates these impacts, is complex. The alternative long-term strategies being developed provide a range of approaches to how and where habitat is conserved. But this analytical framework ensures that the same metrics to calculate take and mitigation will be to evaluate every alternative in an environmental impact statement. That way, comparisons can be made among the alternatives to determine how well they work to minimize and mitigate impacts.

Attachment 1

Calculating the Mitigation for Disturbance

■ Example: Campground Operations

Potential stressors from the use and management of campgrounds are ground-based noise and visual disturbance. These can occur during the 176 day nesting season, every day of the week. The chart on the following page walks through the calculations for determining the total acres impacted by this disturbance activity through the life of the 1997 HCP. The first step is using GIS to identify the potential acres of campground-disturbed habitat (Figure 1); DNR conducted this analysis for all its campgrounds in the analysis area. After the GIS analysis, a series of calculations are made to determine the number of impacted acres in LTFC that must be mitigated for this activity. The numbers provided are for illustration only.

Figure 1. Footprint, Buffer, and P-stage Habitat for One Campground, in Blue Shading; For Illustration Purposes Only

Identify impacted habitat acres

Acres of P-stage habitat in campgrounds, plus 100m buffer	X Average P-stage value across DNR lands	= Acres impacted (weighted)
305	**.34**	**104**

Determine proportion of impacted acres in LTFC

104 acres	X .51 (51% of DNR lands in LTFC)	= **53 acres**

Adjust for time

Number of impacted acres	X Nesting season/ number of camp days	X Number of activity days out of a week	= Impacted acres during nesting season
53	**176/176**	**7/7**	**53**

Calculate over the life of the 1997 HCP

53 impacted campground acres during annual nesting season	X **52** years	= **2,756** time-adjusted acres of P-stage habitat disturbed by campground activities

Attachment 2

Roads as Edges

■ How do Forest Roads Impact Murrelet Habitat?

Forest roads associated with timber harvests act as edges, which in turn affect the success of murrelet nests as discussed earlier in this paper. There is little information about the specific intensity of the edge effect that forest roads alone have on marbled murrelet nests. Some studies using artificial nests near logging roads did not show an increased predation effect (Yahner and Mahan 1997; Otega and Caplan 2002), but these studies were not conducted for canopy-nesting birds in Pacific Northwest forests. In a study from British Columbia using artificial murrelet nests near clearcuts, roads and other forest edges indicated increased corvid abundance and potential predation near artificial edges (Burger and others 2004). Steller's jays in particular are found in greater abundance at edges created by roads and clearings (Masselink 2001; Burger and others 2004; Vigallon and Marzluff 2005). Roads constructed close to or within murrelet habitat are assumed to attract Steller's jays closer into the forest interior (Masselink 2001). As discussed previously, predation impacts have been found to be greatest within 50 meters of a forest edge.

Forest roads initially act as hard edges, and soften over time as they transition back to forest. Many roads are not being actively used, but are a relic of a previous management activity. As roads transition back into forest over the course of several decades, they have corresponding changes in the intensity of their edge effects. There is no accurate method for determining exactly where and how many new forest roads may be needed to access timber harvest sites through 2067. For purposes of analyzing how roads impact the habitat, it is assumed that the current density of DNR forest roads will remain stable through the life of the 1997 HCP. In other words, roads will be abandoned and new roads built, but the overall density will remain unchanged.

■ How is the Road Edge Effect Calculated?

The analytical framework adjusts the value of habitat located within 50 meters of a forest road to reflect potential increases in predation effects. The reduction in habitat value assumed attributable to roads can then be added to the other edge effect factors discussed in this paper. The level of a road's impact, and therefore it's "share" of the edge effect, depends on where the road is located relative to habitat. For example, a road located within an outer, hard edge created by a timber harvest has a concomitant edge effect with that of the harvest area. The road brings no additional predation impacts. But a road bisecting an inner edge is assumed to contribute a portion of the predation edge effect (which for inner, hard edge forests is a 31% reduction in nest success; McShane and others 2004). DNR applied a road edge effect factor throughout the landscape as 15.5% (half of 31%) to reflect these variations.

This road edge effect only applies to a small portion of the analysis area. DNR conducted a spatial analysis to identify how much marbled murrelet habitat is located within 50 meters of active roads. Roads located more than 50 meters from an interior forest were not counted as an edge. Approximately 4.8% of habitat was estimated to be subject to a road edge effect. The number of acres of habitat in different edge conditions, adjusted by other edge factors, can be multiplied by 4.8%, and then multiplied by the road edge factor of 15.5% to determine the road edge effect across the analysis area.

Percent of habitat in interior, or inner-edge LTFC assumed to be within 50 m of a road (4.8%)	x	**Acres of habitat in each edge condition, adjusted by other edge factors (varies depending on the conservation alternative)**	x	**Road edge factor (15.5%)**	=	**Acres of habitat impacted by roads**

The acres of road edge-impacted habitat are added to the total acres that are impacted by harvest and other edge factors. This methodology assumes that as new roads are built, older roads are abandoned, and new habitat grows, keeping the road edge effect consistent through the end of the 1997 HCP. Overall, the portion of the overall impacts from harvest and edges that are attributable to road edges alone is very small. However, this factor is incorporated into the analytical framework and reflected in the formulas used to determine how much mitigation is needed to offset potential impacts from forest management.

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Attachment C-2

Using population viability analyses to assess the potential effects of Washington DNR forest management alternatives on marbled murrelets

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EXECUTIVE SUMMARY

The marbled murrelet (*Brachyramphus marmoratus*) was listed as threatened in Washington, Oregon, and California under the Endangered Species Act in 1992 due to commercial logging of nesting habitat, oil spills, and gill net entanglement. In 2012, the Washington Department of Natural Resources (DNR) initiated the development of a statewide, long-term conservation strategy for marbled murrelets to replace the 1997 Habitat Conservation Plan implemented after initial listing. We used population viability analysis (PVA) approaches to evaluate the potential future (50-year) effects of proposed management alternatives (A – H) on marbled murrelets in Washington. To do so, we developed a stochastic, two-population model linking murrelet demographic rates to forest conditions on DNR and non-DNR lands, and used this model to evaluate each proposed alternative's relative potential to both lead to *Risk* and *Enhance* murrelet populations. Proposed alternatives F and G generally resulted in the greatest number of murrelets and lowest quasi-extinction probabilities, whereas alternative B always resulted in the lowest murrelet population size and highest quasi-extinction probabilities, in both the *Risk* and the *Enhancement* scenarios and at the two spatial scales considered (DNR lands versus state of Washington). Thus, alternative B posed the greatest risk to murrelet populations and alternatives F and G provided the greatest capacity to enhance murrelet populations. For example, at the state scale alternative F was projected to lead to 47 and 248 more murrelets than alternative B under the *Risk* and *Enhancement* scenarios, respectively. Moreover, all alternatives except B were projected to lead to larger murrelet population sizes at year 50 than alternative A (the "no action" alternative), regardless of the spatial scale or scenario (one exception was alternative D in the *Risk* analysis, which resulted in slightly lower murrelet population sizes than alternative A). The

same pattern was generally observed for quasi-extinction probabilities. In a separate sensitivity analysis, we found that, acre-for-acre, murrelet population growth was most sensitive to changes in higher-quality nesting habitat (Pstage 0.89 and 0.62), and while still sensitive, less so to changes in the raw acreage of nesting habitat or nesting habitat configuration (i.e., edge conditions). While we believe our model is sufficiently robust and well-parameterized to help assess how the proposed management alternatives may impact murrelet populations, our results must be considered in light of uncertainly about the effects of future changes in climate and stressors in the marine environment. Future efforts would benefit from using spatially-explicit models that provide (i) geographically-targeted (local) estimates of risk, (ii) prioritize stands for conservation and management, and (iii) generate more realistic insights into how changes in the spatial arrangement of nesting habitat may influence regional murrelet population viability. However, spatially-explicit population models are relatively complex in structure and would benefit from additional research designed to fill key information gaps in our understanding of murrelet ecology and environmental factors influencing murrelet populations.

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INTRODUCTION

The U.S. Endangered Species Act of 1973 (hereafter "ESA") prohibits the "take" of species listed as threatened or endangered (U.S. Congress 1973). In 1982 the ESA was amended to provide flexibility to non-federal land owners with endangered species on their property by granting an "incidental take permit" if they developed a Habitat Conservation Plan (HCP). Under Section 10 of the ESA, HCPs represent planning documents intended to ensure that anticipated take of a listed species will be minimized and mitigated to the maximum extent practicable by conserving the habitat upon which the species depend. Since issuance of an incidental take permit is a federal action, consultation under Section 7 of the ESA must also occur. Through the consultation process the U.S. Fish and Wildlife Service (FWS) determines if the proposed action is likely to lead to "jeopardy" which, according to the regulations implementing the ESA, is when an action "…reasonably would be expected, directly or indirectly, to reduce appreciably the likelihood of both the survival and recovery of a listed species in the wild by reducing the reproduction, numbers, or distribution of that species" (50 CFR §402.02). Although not a statutory requirement, another component of HCP development is addressing whether proposed management alternatives contribute to the recovery of the species as a whole, which is considered to be "an integral product of an HCP…" (USFWS 1996).

HCP negotiations and Section 7 consultations typically consider a wide range of information pertinent to the threatened or endangered species including, but not limited to, current habitat distribution and population trends as well as projections of future habitat and population status. Modeling approaches such as Population Viability Analyses (PVA) are frequently used as part of Section 7 consultations and HCP negotiations to evaluate the potential effects of proposed activities on threatened and endangered species (Harding et al. 2001, Morris et al. 2002). While the ability of PVA approaches to evaluate absolute levels of risk has been questioned, they remain well-suited to compare the relative effects of alternative management strategies on species of concern (Beissinger and Westphal 1998). However, addressing how well different management alternatives both lead to risk and support recovery raises conceptual and practical challenges, even when projections are limited to relative comparisons. Many, if not most, endangered species are declining in numbers and face extirpation due to the cumulative effects of multiple environmental stressors over broad geographic areas that extend beyond the effects of local habitat management within the HCP planning area. In these cases, understanding an alternative's capacity to support recovery may require additional, optimistic assumptions about, for example, improvements to other stressors that impact vital rates. Thus, simultaneously addressing these two questions—namely risk of extirpation/extinction and potential for recovery— as part of Section 7 consultations for endangered species, may require two distinct, yet parallel, modeling efforts. Further, modeling results must often be coupled with consideration of other factors such as geographic distribution for a complete jeopardy analysis.

The marbled murrelet (*Brachyramphus marmoratus*) is a small seabird endemic to the west coast of North America that generally nests in coastal old-growth forests and forages in marine nearshore environments (Meyer et al. 2002). The murrelet was listed as a federally threatened species in Washington, Oregon, and California under the ESA in 1992 primarily because of the loss of older, complex-structured forests to timber harvest, and edge effects from ongoing forest fragmentation (USFWS 1997). However, a host of other factors unrelated to forest management likely impact murrelet populations including marine foraging conditions, disease, oil spills, and by-catch from gill net fishing (Peery et al. 2004, Raphael 2006). Nevertheless, the relative importance of each of these factors in driving recent population declines is not well understood (Falxa and Raphael 2016).

The Washington Department of Natural Resources (DNR) manages forests on "state trust lands" as fiduciary trusts to provide revenue to specific trust beneficiaries, such as schools, universities and other public institutions. In accordance with Section 10 of the ESA, the DNR developed a Habitat Conservation Plan in the late 1990's (WDNR 1997) which was an ecosystem-based forest management plan intended to help the DNR develop and protect habitat for at-risk species, including several federally threatened species (e.g., marbled murrelet and northern spotted owl *Strix occidentalis caurina*), while carrying out forest management and other activities on the state trust lands it manages. In 2012, the DNR formally began a process to amend the 1997 HCP to include a long-term conservation strategy for the marbled murrelet that incorporated a more recent body of scientific information on murrelet biology and habitat needs. The revision of the DNR's HCP seeks to simultaneously address the question of risk and contribution to recovery, a question complicated by the fact that by our analytical framework, habitat on DNR lands contains only about 15% of the estimated carrying capacity for murrelets in Washington (and less in the tri-state area) and multiple, poorly understood environmental stressors likely impact murrelet populations regionally.

To provide insight as to whether forest management alternatives proposed as DNR's long-term conservation strategy may lead to risk or support significant contributions to recovery of murrelet populations in Washington, we used two parallel modeling frameworks—a "*Risk*" and an "*Enhancement*" analysis—that differed in assumptions about future impacts of environmental factors on murrelets beyond habitat change on DNR lands. In the *Risk* analysis, we assumed that current population declines were, in part, a function of recent loss of nesting habitat, and that the current population exceeded the nesting carrying capacity and was expected to decline further because of density-dependent effects. However, we also assumed that undetermined, chronic environmental stressors have contributed to population declines by reducing vital rates (reproduction and survival) such that the population was expected to continue to decline even after the population reached carrying capacity, albeit at a slower rate. While there is uncertainty in the environmental and anthropogenic factors responsible for recent population declines, parameterizing the model such that projected populations declined at approximately the same rate as recent estimates provided some biological realism to the model. This analysis was thus intended to provide a relative comparison of future state-level risk among management alternatives and to provide a general assessment of how risk can be modulated by forest management alternatives on DNR lands, particularly in light of recent population declines (Miller et al. 2012).

While the first analysis provides perspective on risk, estimating differences in risk among alternatives superimposed on expected future, substantial (ca. 5% annual) population declines does not necessarily provide a basis for assessing the extent to which the alternatives may support murrelet recovery. Put simply, we had an *a priori* expectation that potential increases in nesting habitat on DNR-managed lands are unlikely, by themselves, to provide a substantial contribution to the recovery of the considerably larger state-wide population experiencing significant declines likely owing to a host of factors in addition to the nesting habitat on state lands. From the perspective of evaluating a forest management plan, the question of recovery might be cast as: "if other stressors are ameliorated, how do the alternatives differ in their ability of DNR managed-lands to increase local breeding populations?" Therefore, in the *Enhancement* analysis, we developed an alternative parameterization of the model where we assumed that (i) the availability of nesting habitat was the primary cause of recent population declines and the most important factor limiting future population growth, and (ii) that other environmental stressors would not appreciably limit potential future recovery. Thus, as with the *Risk* analysis, murrelets were expected to decline initially at approximately the same rate as estimated with at-sea monitoring, but at some point in the future, the population would reach equilibrium with nesting carrying capacity and that the intrinsic population growth rates were sufficient for the population to increase in response to potential increases in nesting habitat. This second approach, then, provided a more direct means to “credit and debit” the DNR by evaluating potential population response to expected increases and decreases in nesting habitat on DNR lands using population metrics, under the important assumption that other chronic stressors in the environment will not impede recovery.

We implemented this dual modeling approach using a stochastic meta-population model that provided a framework for projecting expected changes in the abundance of murrelets in the state of Washington under various forest management alternatives currently under consideration by DNR and FWS. The model links changes in murrelet population dynamics to expected changes in the quantity, quality, and configuration of nesting habitat on DNR lands over time (that varied among management alternatives) through ecological processes that were reasonably well-supported by the literature and that were agreed upon by DNR and FWS (WDNR 2016). It included two subpopulations linked demographically by dispersal, where the subpopulations represented murrelets nesting on DNR and non-DNR lands. In our model, the dispersal process was spatially implicit; we did not explicitly consider the complex, landscape-scale distribution of murrelet nesting habitat on different landownerships in the state of Washington because many of these processes are not well understood and fully addressing these complexities was deemed beyond the scope of the Conservation Strategy negotiations by the involved resource agencies.

The metapopulation model made a number of additional simplifying assumptions as the secretive behavior and marine habitats of marbled murrelets challenges field studies needed to parameterize the model described below. Thus, and as is the case with all PVA exercises, projections of risk should not be considered as absolute estimates, and only be interpreted as a way to compare the relative consequences of different scenarios (Beissinger and Westphal 1998). However, our objective was to develop a population model where differences in projected risk among management alternatives were sufficiently robust to violations of assumptions and uncertainty that the involved agencies could identify which alternative best met joint objectives. More broadly, we sought to understand how using parallel *Risk* and *Enhancement* analyses could facilitate management decisions and endangered species conservation while meeting legal obligations of the Endangered Species Act and DNR's policy goal of making a "significant contribution" to murrelet conservation. *In doing so, we recognize it is beyond our purview to provide recommendations as to whether individual alternatives impact murrelets such that "…survival and recovery in the wild is appreciably reduced" or whether they benefit murrelet populations to the point that they "contribute to the recovery of the species as a whole".* While we do highlight when, and under what circumstances, an individual alternative might increase/decrease risk or may increase the likelihood of recovery via population gains, we make no judgments as to whether modeled impacts on populations are sufficient to meet specific FWS regulatory criteria related to jeopardy or population recovery. While this distinction is subtle, we believe it is an important one.

METHODS

Model Structure and Parameterization

Matrix Model Structure. We developed a female-based, stochastic meta-population model that employed a one-year time step in accordance with the annual breeding cycle of marbled murrelets (Nelson 1997). Each of the two subpopulations (DNR and non-DNR lands) contained five stages classes: juveniles, 1-year old subadults, 2-year old subadults, adult (≥3-year olds) nonbreeders that did not breed because of insufficient nesting habitat, and adult breeders (≥3-year olds; Figure 1). The five stage classes were indexed $x = 1, 2, \ldots, 5$ in the order presented above, and DNR and non-DNR lands were indexed as $L = 1$ and 2, respectively. Note that, at times, the ≥1-year-old stage classes (non-juveniles) are collectively referred to as after-hatch-year (AHY) individuals for convenience. Model parameters are defined in Table 1, and the rationale for assumptions behind the selected model structure and parameter values are described throughout the next several sections.

The life-cycle diagram can be expressed mathematically as a matrix model that determines the number of individuals in each stage class at time $t + 1$ based on the number of individuals in each stage class in year t (Caswell 2001, Morris and Doak 2002). The murrelet meta-population model $\mathbf{A}_t$ consisted of four submatrices that defined local demographic and dispersal processes (Hunter and Caswell 2005):

$$\mathbf{A}_t = \begin{bmatrix} \mathbf{A}_{\mathbf{1},\mathbf{t}} & \mathbf{M}_{\mathbf{2},\mathbf{t}} \\ \mathbf{M}_{\mathbf{1},\mathbf{t}} & \mathbf{A}_{\mathbf{2},\mathbf{t}} \end{bmatrix}$$

The two submatrices on the main diagonal ($\mathbf{A}_{\mathbf{L},\mathbf{t}}$) governed local demographic processes on DNR and non-DNR lands, denoted $\mathbf{A_{1,t}}$ and $\mathbf{A_{2,t}}$, respectively. The two submatrices in the off-diagonal determined murrelet dispersal between the two landownerships where the submatrix governing dispersal from DNR lands to non-DNR lands was $\mathbf{M_{1,t}}$ and the submatrix governing dispersal from non-DNR to DNR lands was $\mathbf{M_{2,t}}$ (the dispersal matrices are described in more detail below). The demography submatrices were structured as follows:

$$\mathbf{A_{L,t}} = \begin{bmatrix} 0 & 0 & s_{3,L,t}g_{3,L,t}bf_{L,t} & s_{4,L,t}g_{4,L,t}bf_{L,t} & s_{5,L,t}(1-g_{5,L,t})bf_{L,t} \\ s_{1,L,t} & 0 & 0 & 0 & 0 \\ 0 & s_{2,L,t} & 0 & 0 & 0 \\ 0 & 0 & s_{3,L,t}(1-g_{3,L,t})(1-d_{L,t}) & s_{4,L,t}(1-g_{4,L,t})(1-d_{L,t}) & s_{5,L,t}g_{5,L,t} \\ 0 & 0 & s_{3,L,t}g_{3,L,t}(1-d_{L,t}) & s_{4,L,t}g_{4,L,t}(1-d_{L,t}) & s_{5,L,t}(1-g_{5,L,t}) \end{bmatrix}$$

In these matrices, $s_{x,L,t}$ represented the annual survival rates, $g_{x,L,t}$ represented the probability of transitioning (transition rate) from stage class x (conditional on survival and population fidelity), $d_{L,t}$ was the annual dispersal rate, b was the breeding probability, and $f_{L,t}$ was nest success. Note that $g_{1,L,t}$ and $g_{2,L,t}$ were always equal to 1 and are therefore not presented in either the life cycle diagram or the matrix model.

Parameterizing Survival Rates ($s_{x,L,t}$). The model was parameterized with an annual survival rate of 0.87 and 0.90 in the *Risk* and *Enhancement* analyses, respectively, for after-hatch-year females ($s_{2,L,t}$ to $s_{5,L,t}$) based on a mark-recapture study of 331 individual marbled murrelets in central California (Peery et al. 2006b) (Table 1). A pooled survival rate was used for these four stages classes because it was not possible to distinguish beyond juvenile versus after-hatch-year at the time of the mark-recapture study. We assumed the annual juvenile survival (s_1 and s_6) was 70% of after-hatch-year survival based on differences in survival rates between these stage classes in other alcid species (insufficient juveniles were captured to estimate juvenile survival directly; Peery et al., 2006a).

Parameterizing Breeding Probabilities (b,$f_{L,t}$*).* We treated the parameter *b* as the expected proportion of individuals in the breeding stages (i.e., that were "in possession" of a nest site) that actually nested in each year. We assumed that some fraction of breeders did not nest each year because, in seabirds, some individuals typically forgo nesting due to, for example, poor foraging conditions (Peery et al. 2004). The proportion of breeders has been estimated using radio-telemetry in the state of Washington, but estimates are likely biased low as a result of transmitter effects (Peery et al., 2006b, M. G. Raphael *pers. comm.*). A similar study in central California (Peery et al. 2004) used assays of plasma calcium (an indicator of eggshell deposition) and vitellogenin (an egg yolk precursor) to identify radio-marked individuals that did not nest but were physiologically in breeding condition at the beginning of the breeding season (indicating they likely would have nested in the absence of radio-tagging). Peery et al. (2004) found that 77% of sampled murrelets either initiated nesting or were physiologically in breeding condition. However, some individuals that were not detected nesting and were not in breeding condition may have nested and failed prior to radio-tagging. Thus, we used *b* = 0.90 as a reasonable estimate for the proportion of breeders in the state of Washington. Note that we assumed *b* was constant across years and equal 0.90 in both landownerships. However, we incorporated the effects of environmental variability on *b* implicitly by treating expected fecundity ($m_{L,t}$: the product of the proportion of breeders, *b,* and nest success, $f_{L,t}$, divided by two; see below) as a random beta-distributed variable in the population projection model as described above.

Modeling Transition Probabilities ($g_{x,L,t}$). Transition rates ($g_{x,L,t}$) provided the primary mechanism linking the demographic model to potential changes in the availability of nesting habitat resulting from forest management activities. Transition rates for the 2-year subadult and nonbreeding stages into the breeding stage class ($g_{3,L,t}$ and $g_{4,L,t}$, respectively) were calculated based on the number of individuals seeking nests sites relative to the number of available nests in year t + 1 in landownership L. For example, if the number of murrelets seeking nest sites (i.e., 2-year old subadults plus nonbreeders) was less than the number of available nest sites, then $g_{3,L,t}$ and $g_{4,L,t}$ = 1, such that all murrelets found nest sites. If the number of murrelets seeking nest sites exceeded the number of available nest sites, then $g_{3,L,t}$ and $g_{4,L,t}$ < 1 such that not all 2-year old subadults and nonbreeders in the population become breeders in year t + 1. Thus, if the number of nest sites in a given landownership ($K_{L,t}$) declined, for example as a result of timber harvesting, transition rates into the breeding class would also decline and fewer individuals would reproduce (effectively reducing the expected population growth rate). Conversely, if the number of nest sites increased (for example, as a result of forest growth and maturation), transition rates into the breeding class would tend to increase and more individuals would reproduce (effectively increasing the expected population growth rate). Mathematically, transition probabilities for landownership L in year t and were calculated as follows:

$$g_{3,L,t} = g_{4,L,t} = \frac{K_{L,t+1} - s_{5,L,t} n_{5,L,t} (1 - g_{5,L,t})}{s_{3,L,t}, n_{3,L,t} + s_{4,L,t} n_{4,L,t}}$$

The numerator in this equation represented the number of available nest sites (carrying capacity minus the number of surviving breeders from the previous year), whereas the denominator represented the number of potential new breeders seeking nest sites (surviving 2-year subadults and nonbreeders from year *t*).

Reductions in the number of nests sites ($K_{L,t}$) could also impact population growth by causing some breeders in possession of a nest site in year *t* to transition to the nonbreeder stage in year *t* + 1 ($g_{5,L,t}$):

$$g_{5,L,t} = 1 - \frac{K_{L,t+1}}{K_{L,t}}$$

For example, if half of existing nest sites were lost in year *t*, half of the surviving breeders in year *t* would transition to the nonbreeder stage in year *t* + 1. As described above, nonbreeders could transition back to the breeding stage if nests became available (e.g., through forest growth), but the model assumed that breeders that lost their nest sites as a result of habitat loss became nonbreeders for at least one year.

Parameterizing Dispersal Rates ($d_{L,t}$*) and Modeling Dispersal Processes.* Modeled murrelet populations in the two landownerships were linked demographically by the dispersal of individuals, where the annual dispersal rate from DNR to non-DNR lands, and from non-DNR to DNR lands, was defined as $d_{1,t}$ and $d_{2,t}$, respectively. The submatrix representing dispersal from land ownership *L* was structured as follows:

$$\mathbf{M}_{L,t} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & s_{3,L,t}g_{3,L,t}d_{L,t} & s_{4,L,t}g_{4,L,t}d_{L,t} & 0 \end{bmatrix}$$

For example, if $L = 1$, then the matrix $\mathbf{M}_{\mathbf{1},t}$ would represent dispersal from DNR to non-DNR lands in year *t*. The model assumed that dispersal movements were made by 2-year subadults and nonbreeders as these individuals transitioned to breeding stages in either landownership; juveniles and 1-year subadults remained in their natal population until they were old enough to breed. Individuals in breeding stages were assumed to remain in their respective populations such that "breeding dispersal" was effectively zero, a reasonable assumption based on anecdotal observations of the re-use of the same nesting site by murrelets in consecutive years (R. T. Golightly *pers. comm.*) as well as generally strong breeding fidelity in alcids (Gaston and Jones 1998). Dispersal rates between DNR and non-DNR lands are unknown, but approximately 85% of existing carrying capacity for murrelets in Washington occurs on non-DNR lands and 15% occurs on DNR lands. Thus, if we assume natal dispersal is random with respect to landownership, d_1 would be 0.85 and d_2 would be 0.15. However, a cap to the number of dispersers, and thus the dispersal rates was imposed by the number of available nest sites in the receiving population. Thus, if the number of dispersers calculated based on the dispersal rate exceeded the number of available nest sites in the receiving population, the "realized" dispersal rate was adjusted as follows for murrelets dispersing from DNR lands:

$$d_{1,t} = \frac{K_{2,t+1} - (s_{3,2,t}n_{3,2,t} + s_{4,2,t}g_{4,2,t}n_{4,2,t} \; + \; s_{5,2,t}[1 - g_{5,2,t}]n_{5,2,t})}{s_{3,1,t}(1 - g_{3,1,t})n_{3,1,t} + s_{4,1,t}(1 - g_{4,1,t})n_{4,1,t} \; + \; s_{5,1,t}g_{5,1,t}n_{5,1,t}}$$

Here, the numerator represents the number of available nest sites on non-DNR lands in year *t* + 1 after "local" recruitment by resident 2-year subadults and nonbreeders, whereas the denominator represents the number of available recruits from DNR lands in year *t* + 1. The analogous adjustment for dispersal rates from non-DNR lands was made as follows:

$$d_{2,t} = \frac{K_{1,t+1} - (s_{3,1,t}n_{3,1,t} + s_{4,1,t}g_{4,1,t}n_{4,1,t} + s_{5,1,t}[1 - g_{5,1,t}]n_{5,1,t})}{s_{3,2,t}(1 - g_{3,2,t})n_{3,2,t} + s_{4,2,t}(1 - g_{4,2,t})n_{4,2,t} + s_{5,2,t}g_{5,2,t}n_{5,2,t}}$$

As with local recruitment into the breeding stage, the model assumed that dispersing individuals selected nesting habitat in the destination population independent of habitat quality and edge conditions.

Initial Population Sizes ($n_{x,L,0}$*).* We set the population size in year *t* = 0 of model projections equal to one-half of the mean annual population size (our model was female-based and we assumed a 50% sex ratio) for the state of Washington estimated with at-sea monitoring from 2011 to 2015 (*n* = 3,616 individuals; Falxa et al. 2016). While more recent surveys for murrelets have been completed in Washington, 2015 was the last year that a state-wide census was completed. The total number individuals (i.e., females) was allocated to DNR and non-DNR lands in proportion to the estimated carrying capacity of nesting habitat that exists on each of the two land ownerships (0.15 and 0.85, respectively), which yielded a total 542 individuals in the DNR subpopulation and 3,074 individuals in the non-DNR subpopulation. Within each subpopulation, we allocated individuals to the stage classes in accordance with the expected stable age distribution associated with a deterministic version of the matrix model structure that was parameterized as described above. Initially, nonbreeding and breeding stages ($n_{4,L,0}$ and $n_{5,L,0}$, respectively) were pooled (both classes treated as "adults") when determining the stage distribution in year *t* = 0. Adults were then allocated to the nonbreeding and breeding stages in year *t* = 0 as described below such that the number of adults exceeded the carrying capacity to a degree that provided reasonable correspondence between modeled population trajectories and observed trends in the Washington population.

Evaluating "*Risk*" and "*Enhancement*"

We parameterized the matrix model in both the *Risk* and *Enhancement* analyses using the values described above and listed in Table 1. We assumed that 40% of individuals of breeding age ($\geq$3 years old) were in the nonbreeding stages in year $t = 0$ for each subpopulation and thus that the number of adult-aged individuals exceeded nesting carrying capacity for both analyses (see below). As described above, we made this assumption to reflect nesting habitat loss in the state of Washington that may have resulted in a nonbreeding component of the population. Moreover, associated density dependent effects on population growth allowed projected populations to decline in the initial years of the modeling period in reasonable accordance with recent observed declines (see below). The after-hatch-year annual survival rate was set to 0.87 and 0.90 in the *Risk* and *Enhancement* analyses, respectively. Higher survival rates in the *Enhancement* than *Risk* analysis allowed projected populations in this scenario to increase in response to potential gains in nesting habitat. For the portion of the *Enhancement* analysis focusing on DNR lands only, we assumed no dispersal between subpopulations to highlight "debits" and "credits" of forest management alternatives for losses and gains in nesting habitat, respectively, using population metrics.

Together, these assumptions yielded deterministic projections of population growth under constant habitat conditions that were reasonably consistent with the recent estimates of population trends (5% annual decline) in the initial years of the population projection. As the breeding-age component of modeled populations approached nesting carrying capacity, the rate of population growth increased in both the *Risk* and *Enhancement* analyses. The expected population growth rate stabilized around year 15 under the *Risk* analysis, but stabilized below 1 (a population growth rate of 1 is indicative of a stable population), and the simulated populations were thus expected, on average to decline (by approximately 1.5% annually) over the projection period. By contrast, population growth stabilized above 1 under the *Enhancement* analysis, and thus we expected small population increases (approximately 1% annually) over the modeling period.

Modeling the Impact of Nesting Habitat Change on Marbled Murrelet Populations

As described above, we modeled the potential effects of forest management alternatives on marbled murrelet population dynamics by linking the maximum number of breeders (carrying capacity, $K_{L,t}$) and nest success rates ($f_{L,t}$) to forest conditions (i.e., nesting habitat) present in the two landownerships in each year *t*. We assumed that availability of nesting habitat limits murrelet breeding opportunities and that forest fragmentation reduces nest success via edge effects. Specific measures of nesting habitat considered were nesting habitat (1) area, (2) quality, and (3) configurations (WDNR 2015). These three measures were initially quantified at the forest stand scale using DNR’s spatially-explicit forest inventory database which contains information on mapped stands of known acreage such as characteristics of age, origin (natural vs. planted), and composition (Douglas-fir vs. shade-tolerant). Stand-level characteristics were ultimately aggregated to develop estimates of the maximum number of breeders and expected nest success in each landownership. The analytical methods, rationale, and assumptions used to derive estimates of carrying capacity and nest success are described below in conceptual terms. For a more detailed, mathematical explanation, we direct the reader to Appendix A.

Effects of Forest Conditions on Carrying Capacity ($K_{L,t}$*).* The model imposed a limit to the number of breeders ($K_{L,t}$) in each landownership based on the total amount, quality, and configuration of nesting habitat in each year t. Nesting carrying capacity ($K_{L,t}$) was assumed to be positively related to the amount of nesting habitat present on landownership L in year t in a one-to-one manner; for example, a forest stand 100 ha in size would be expected to contain twice as many breeding murrelets as a stand 50 ha in size, all other factors being equal (i.e., nesting habitat quality and configuration). In Washington, a positive association has been observed between radar counts of murrelets flying inland and the amount of late-seral stage forest at the watershed scale, and the slope of this relationship is approximately one (Raphael et al. 2002). Nesting density was assumed to be related to stand-level “habitat quality” based on generalized probabilities of murrelet use that were associated with stages of successional development in DNR-managed forest in southwest Washington (Raphael et al. 2008). Based on DNR’s forest inventory, stands were assigned to one of six nesting habitat quality categories (“Pstage”), non-habitat (Pstage = 0) and five classes of habitat with Pstage values 0.25, 0.36, 0.47, 0.62, 0.89. In the previous version of the report, the Pstage value at sites occupied by murrelets was reassigned to an additional Pstage class, Pstage = 1; in the current version of the report we did not redistribute the Pstage value at occupied sites to 1 but instead used the underlying Pstage value (0.25, 0.36, 0.47, 0.62, or 0.89). This revised approach more precisely reflects estimated habitat quality and permits increases in carrying capacity to occur at occupied sites through forest maturation as forest stands transition into higher Pstage classes. Classification was based on stand age, origin (natural vs. planted), and species composition, where (i) older stands were assumed to have greater nesting densities than younger stands, (ii) naturally-regenerated stands (unlike planted) were assumed to be capable of developing as habitat within the analysis period, and (iii) stands dominated by western hemlock (*Tsuga heterophylla*) were assumed to develop into suitable habitat and thus greater nesting densities at an earlier age than stands dominated by Douglas-fir (*Pseudotsuga menziesii*). Together these three variables were assumed to represent the development of key murrelet nesting habitat characteristics such as large trees with large limbs and complex canopy structure. In our population model, the Pstage value represented the stand's maximum nesting density where, for example, ~3.5 acres of Pstage 0.25 provide the same nesting opportunities as one acre of Pstage 0.89.

Maximum nesting density was also influenced by edge effects, where availability of nest sites (and thus nesting density), was assumed to be lower in portions of stands adjacent to edges with non-habitat. Wind-throw as well as hotter, drier microclimate at the edge of young stands created by timber harvest can lead to the mortality of platform-bearing trees as well as epiphyte mortality that reduces platform abundance in surviving trees (Chen et al. 1992; van Rooyen et al. 2011). Edge effects were assumed to occur when a stand of suitable habitat (Pstage > 0) occurred adjacent to a stand dominated by trees < 80' (approximated as <40 years old) and were categorized based on the condition of adjacent young forests as "hard" (<40' tall approximated as <20 years old) or "soft" (40'-80' tall). Empirical values of tree density and suitable platform abundance from van Rooyen et al. (2011) formed the basis for adjustments to nesting density (Pstage) for the two edge types, 0.25 adjacent to hard edges and 0.60 at soft edges. Habitat in small, often linear fragments that were entirely edge, called *Strings* was assumed to have no value. Edge effects on larger habitat patches with areas over 100 meters from edge are assumed to be greatest near edges and decline with distance, generalized to "outer" and "inner" edges within 50 meters and between 50 and 100 meters from edge (Chen et al. 1992). Full effects were assumed to occur in outer edges, half-effects were assumed for inner edges, and "interior" habitat

>100 m from edge was assumed to be unaffected. Thus as informed by DNR's spatially-explicit forest inventory, nesting density was estimated for each factorial combination of Pstage (five classes), edge distance (three classes: outer, inner, interior), and edge type (hard and soft). This process resulted in 20 combinations of five Pstage classes by edge-distance (outer, inner) and edge-type (hard, soft) plus five Pstage classes in interior habitat providing 25 different nesting density adjustments applied to current and alternative-specific projected future habitat maps. For example, nesting density was assumed to be 14.2 times greater in Pstage = 0.89, interior forest than in Pstage = 0.25 subject to the hard, outer edge effect of 0.25 (14.2 = 0.89 / (0.25*0.25). Pstage and edge adjustments for non-DNR lands followed the assumptions of Raphael et al. (2008) and were held constant over the modeling period.

Original nesting carrying capacity estimates (see Appendix A) based on the number of adult female murrelets based on at-sea surveys failed to yield population trajectories consistent with recent ~5% annual declines in the state (Falxa et al. 2016). Using deterministic simulations, we found that when we set nesting carrying capacity such that 40% of adult murrelets were non-breeders (i.e. the population was above carrying capacity), initial simulated population declines better approximated recent observed ~5% annual declines. Therefore we set initial nesting carrying capacity ($K_{L,0}$) to equal the number of adult breeders on each landownership L ($n_{5,L,0}$), which was 60% of the number of female adult murrelets in year 0 based on a stable age distribution (Table 1). In each subsequent year ($t \geq 1$), carrying capacity $K_{L,t\geq1}$changed based on projected losses (from harvesting) or gains (through forest growth) in nesting habitat in each Pstage by edge-type and distance combination and the nesting density relationships described above. Moreover, because a single nesting carrying capacity was considered for each landownership that reflected aggregate habitat conditions, we assumed that recruiting murrelets choose nests sites randomly with respect to edge type and Pstage (i.e., they recruit into habitat in proportion to the abundance of potential nest sites it is assumed to provide).

Effects of Forest Conditions on Nest Success ($f_{L,t}$*).* The model also linked population growth rates to nesting habitat conditions by treating nest success rates (number of female offspring produced per nesting female) in landownership *L* and year *t* ($f_{L,t}$) as a function of the distribution of interior, inner edge, and outer edge forest in the landownership. Nest success was assumed to be greatest where edge effects were absent and to be reduced where nesting habitat occurred adjacent to a hard edge, with inner edges assumed to promote higher nest success than outer edges. Soft edges were assumed to have no influence in nest success (Raphael et al. 2002, Malt and Lank 2009). Estimates of nest success rates in soft- or non-edge influenced forest (0.550) and outer edge (0.380) were drawn from the upper and lower bounds assumed for this parameter in demographic analyses conducted by McShane et al. (2004). An intermediate value of 0.465 was assumed for nest success in inner edge near hard edges. In sum, greater relative amounts of edge habitat under a given management alternative were expected lead to a greater fraction of the population nesting near edges, lower mean nest success, and lower population growth rates.

Forest Management Alternatives

We considered eight forest management alternatives (A-H), each involving different approaches to timber harvesting and habitat conservation on DNR-managed land in western Washington (WDNR and USFWS 2018). Each alternative was built around *long-term forest cover* (LTFC), areas of existing conservation commitments made under the HCP (e.g., high-quality spotted owl habitat, riparian management zones), DNR’s Policy for Sustainable Forests and state law. The alternatives then variously add LTFC to further conserve and restore murrelet habitat. The abundance, configuration, and location of this murrelet-specific LTFC differs among alternatives, reflecting a range of conservation approaches. All alternatives provide for new habitat growth through the life of the HCP. Common among alternatives, initial (t = 0) forest conditions were set to current conditions on DNR-managed lands (DNR database and landscape models of potential murrelet nesting habitat) and other landownerships in Washington (Raphael et al. 2016). Projections of future habitat conditions over the 50-year modeling period were conducted by DNR using the Forest Vegetation Simulator (FVS), where differences in harvest and conservation among the management alternatives led to different expected trajectories in the amount, quality and configuration of murrelet nesting habitat on the landscape, and thus differences in carrying capacity and nest success among the alternatives (Figure 2). The eight alternatives are more thoroughly defined elsewhere (dnr.wa.gov/mmltcs), but they, and a baseline scenario (i.e., static forest conditions) are briefly summarized below:

1. **Alternative A** is the "no-action" alternative, approximating continued DNR operations as authorized under the 1997 HCP. This alternative includes approximately 600,000 acres of LTFC, with murrelet-specific conservation including: all occupied sites as delineated by HCP-directed surveys, with a 100-meter buffer; all reclassified habitat in OESF; all reclassified habitat in the Straits, South Coast and Columbia planning units that has not been identified as "released" for harvest under the interim strategy; in the North Puget and South Puget planning units, all suitable habitat that has not been identified as "released" for harvest subject to the 2007 concurrence letters, all newly identified habitat, and all potential habitat that has a Pstage value >0 in decade 0.

2. **Alternative B** focuses on protecting the known locations of marbled murrelet occupied sites on DNR-managed land. Under this alternative, LTFC totals approximately 576,000 acres, and includes occupied sites delineated by the 2008 Science Team recommendations (Raphael et al. 2008). This approach results in approximately 16,000 acres more than the HCP delineations used by Alternative A, as well as occupied sites identified by DNR staff in the North and South Puget planning units. This is the only alternative that does not provide buffers on occupied sites.
3. **Alternative C** is designed to protect occupied sites and current habitat as well as grow new habitat over the life of the HCP. LTFC totals approximately 617,000 acres. This alternative contains both marbled murrelet "emphasis areas" and "special habitat areas." Seven emphasis areas from 4,100 to 15,600 acres are identified in strategic landscapes for the purpose of protecting and reducing fragmentation around occupied sites, and developing future marbled murrelet habitat. Twenty special habitat areas, 40 to 8,000 acres, are generally smaller than emphasis areas and are designed to increase murrelet productivity by reducing edge and fragmentation around more isolated occupied sites that are not within an emphasis area. Outside of emphasis or special habitat area boundaries, this alternative will also buffer all other existing occupied sites and will maintain all higher quality habitat (Pstage value 0.47 and greater).
4. **Alternative D** concentrates conservation into thirty-two special habitat areas, 40 to 14,400 acres. LTFC totals approximately 618,000 acres. All acreage within special habitat areas is designated as LTFC. Special habitat areas are designed to increase the productivity of existing occupied sites by increasing habitat abundance and reducing edge effects. They include: strategically located occupied sites with 100-meter buffers;

adjacent Pstage habitat (both existing and expected to develop through 2067); adjacent, non-habitat areas intended to provide security to existing and future habitat (security forests). The boundaries of the special habitat areas were identified based on existing landscape conditions (management history, watershed boundaries, natural breaks or openings). Because of its focus on reducing fragmentation around existing, occupied sites, Alternative D would allow more acres of potential habitat (habitat that has or will develop a Pstage value) to be harvested throughout the analysis area than Alternative C. However, the overall amount of LTFC is similar under Alternatives C and D.

5. **Alternative E** combines the conservation approaches of Alternatives C and D, for a total of approximately 622,000 acres of long-term forest cover. This alternative includes the following murrelet-specific conservation: occupied sites, with 100 meter buffers; all habitat with a Pstage value of 0.47 and greater throughout the analysis area; emphasis areas as designated under Alternative C; special habitat areas as designated under Alternative D (where emphasis areas and special habitat areas overlap, emphasis area will be the designation).

6. **Alternative F** proposes to apply the conservation recommendations presented in the 2008 Science Team report (Raphael et al. 2008), which evaluated conservation opportunities in the four coastal HCP planning units and recommended the establishment of 45 marbled murrelet management areas of up to 15,500 acres. It also applied the principles of Raphael et al. (2008) to establish 20 similar areas of up to 47,400 acres in the North and South Puget planning units. In total approximately 734,000 acres of LTFC is designated under this alternative. All occupied sites would be protected with a 100-meter buffer. Additionally, all Old Forest in the OESF would receive a 100-meter buffer.

Existing, mapped low quality northern spotted owl habitat in designated owl conservation areas (nesting/roosting/foraging, dispersal and OESF) is included as LTFC (Alternatives A through E only include high quality owl habitat as LTFC).

7. **Alternative G** is a new alternative, added between the DEIS and RDEIS. This alternative was developed based on comments received on the DEIS from federal and state agencies, environmental groups, and various individuals. Alternative G includes approximately 643,000 acres of LTFC. This alternative includes, emphasis areas, special habitat areas, and marbled murrelet management areas and applies 100 meter buffers to all occupied sites. Alternative G includes the following murrelet specific conservation lands: all habitat with a Pstage value of 0.47 and greater throughout the analysis area; in the OESF, all habitat with a Pstage greater than zero in decade zero; Emphasis Areas as designated under Alternative C; special habitat areas as designated under Alternative D (where emphasis areas and special habitat areas overlap, an emphasis area will be the designation); areas where the Pstage model did not identify potential existing habitat or applied a lower Pstage value than thought appropriate based on expert opinion (WDFW Polygons); the marbled murrelet management area in the Elochoman block, as drawn for Alternative F, managed as an Emphasis Area; and the following marbled murrelet management areas in the North Puget Planning Unit: Spada Lake/Morningstar, Whatcom, Middle Fork Hazel/Wheeler Ridge, Marmot Ridge.
8. **Alternative H** is DNR's preferred alternative. Alternative H is based on direction from the Board of Natural Resources to minimize impacts, offset impacts and address uncertainty, and reduce disproportionate financial impacts to trust beneficiaries. Alternative H minimizes impacts by conserving all existing occupied sites, capturing

existing habitat within special habitat areas, and metering harvest of habitat outside conservation areas in strategic locations. Metering delays harvest of a portion of habitat until the second decade of the modelling period. Metering is designed to maintain nesting carrying capacity on DNR-managed lands such that capacity always equals or exceeds baseline conditions. Alternative H offsets impacts and addresses uncertainty by applying 100-meter buffers on all occupied sites, locating special habitat areas in strategic locations, and increasing the amount of interior forest habitat in LTFC. This alternative reduces disproportionate financial impacts identified in the DEIS in Pacific and Wahkiakum counties under Alternatives C through F by placing less conservation on State Forest lands in these counties. Alternative H includes approximately 610,000 acres of LTFC.

9. **Baseline** represents a static habitat scenario, where the raw amount of murrelet nesting habitat that presently exists on DNR lands excluding habitat located in "strings" (166,410 acres) remains constant over the 50-year modeling period. Carrying capacity ($K_{1,t}$ = 217) and nest success ($f_{1,t}$ = 0.5343) also remain fixed. Although it is biologically unrealistic, the baseline scenario offers a useful benchmark by which to compare scenarios with changing habitat conditions.

In addition to the eight proposed alternatives, the DNR and USFWS proposed an additional analysis which would show how the modeled murrelet population on DNR lands might respond to Alternative H *without* the delayed harvest implementation (**Alternative H – 'no meter'**) under both *Risk* and *Enhancement* scenarios. This additional exploratory scenario sought to gauge how a more rapid rate of habitat decline (but less prolonged decline) might influence projected murrelet populations.

For the eight primary alternatives and one exploratory alternative, forest conditions on non-DNR lands were assumed to be stationary over the modeling period. While we recognize that habitat conditions on non-DNR lands are not static, we lacked sufficient information for non-DNR lands to project habitat changes over time. Because our modeling objective was to evaluate how changes in habitat conditions on DNR lands may influence murrelet populations over time, it was appropriate to evaluate the range of alternatives in the context of the current conditions on non-DNR lands. Although this assumption is clearly unrealistic, some habitat will be lost to harvest and natural disturbances, and habitat will develop on federal lands reserved from harvest under the Northwest Forest Plan (Raphael et al. 2016), it was adopted because it simplified presentation and interpretation of population responses to changes on DNR-managed land which contain about 15% of murrelet nesting carrying capacity in Washington according to our analytical model.

Model Projections, Stochasticity, and Estimating Risk

Model Projections. We projected the model forward in time as follows:

$$\mathbf{n}_{t+1} = \mathbf{A}_{\boldsymbol{t}} \cdot \ \mathbf{n}_t$$

where $\mathbf{n}_t$ was a 10 by 1 vector of murrelet abundance in the five stage classes $x = 1,2,\ldots,5$ and two landownerships $L = 1, 2$ in year t, and $\mathbf{A}_{\boldsymbol{t}}$ was the matrix of vital rates (described above). The vector of population sizes $\mathbf{n}_1$ was:

$$\mathbf{n}_1 = \begin{bmatrix} 83 \\ 52 \\ 46 \\ 145 \\ 217 \\ 472 \\ 293 \\ 260 \\ 819 \\ 1229 \end{bmatrix}$$

where the first five elements represent the number of juveniles, 1-year subadults, 2-year subadults, and adults (nonbreeders and breeders) on DNR lands assuming a stable age distribution. The second five elements would be the number of individuals in each of these stage classes on non-DNR lands under the same sets of assumptions. The number of adults in the nonbreeding and breeding classes (the fourth and fifth elements for each landownership) were allocated based on deterministic carrying capacity simulations (see above).

Incorporating Environmental Stochasticity. The model incorporated the effects of stochasticity by allowing survival and reproductive rates to vary randomly from year to year. After-hatch-year survival rates in year *t* were selected randomly from a beta distribution. Selecting survival rates from a beta distribution ensured that survival rates fell between 0 and 1. As discussed above, we set the mean value for annual survival for after-hatch-year murrelets to 0.87 and 0.90 in the *Risk* and *Enhancement* analyses, respectively, based on mark-recapture studies in California (Peery et al. 2006b). Annual variability in survival has not been estimated rigorously for marbled murrelets, but setting the variance in annual survival $[var(s)]$ to 0.004 resulted in few years with survival < 0.75, and thus provided a reasonable degree of biological realism. Frequent survival rates below 0.75 seemed implausible given the modest annual variability in population size estimated from at-sea surveys (Falxa et al. 2016). Juvenile survival in year *t* was set to 70% of after-hatch-year survival such that these two rates are assumed to co-vary perfectly. Stochasticity in reproduction was modeled by first calculating expected fecundity (the number of female juveniles per female adult denoted $m_{1,t}$ and $m_{2,t}$ for DNR and non-DNR lands, respectively) which is simply the product of the expected proportion of females that breeders (b) and nest success ($f_{L,t}$) divided by 2 (because approximately half of fledging juveniles are female). Fecundity was then randomly selected in year *t* from a beta distribution with an expected value of $m_{L,t}$ and a variance $[var(m)]$. An attempt was made to use the variance in reproductive data from central California, but simply using a value of 0.016 for $[var(m)]$ yielded more realistic projections. Fecundity on DNR and non-DNR lands was assumed to be perfectly correlated and vary with the same magnitude. Survival and fecundity were assumed to co-vary independently among years since these vital rates appear to be driven by different environmental processes (Peery et al. 2006b, Becker et al. 2007). The variances of $[var(s)] = 0.004$ for survival and $[var(m)] = 0.016$ for reproduction resulted in a mean coefficient of variation (CV) in simulated populations over the first 15 years (CV = 0.201) that aligned with expectations based on the process variance observed in murrelet at sea counts in WA from 2001 to 2015 (CV = 0.203), when we used demographic values and nesting carrying capacity that led to approximately 5% annual declines ($s_{\geq 2,L,t}$ = 0.87 and $d_{L,t} = 0$).

Quantifying Population Risk. For each of the management alternatives (see below), we projected 10,000 simulated populations forward in time for *t* = 50 years (where *t* = 0 represented present conditions). To assess patterns of risk, we estimated (i) the mean change in population size between *t* = 0 and 50 and (ii) the "quasi-extinction probability", defined as the proportion of simulated populations where $\sum_{i=1}^{x} n_{x,L,50}$ was lower than subjectively defined quasi-extinction thresholds. Quasi-extinction thresholds were set to one half, one quarter, one eighth, and one sixteenth of the starting population size (i.e., $\sum_{i=1}^{x} n_{x,L,0}$).

Sensitivity Analysis

While the scenario-based analysis of murrelet population viability allowed us to compare potential effects of proposed forest management alternatives, the relative influence of changes in individual habitat classes (e.g., inner edge vs. interior forest) on murrelets was confounded because the alternatives included simultaneous changes in many or all habitat classes each year throughout the 50-year modeling period. We developed a sensitivity analysis to explore the relative influence of each the nine habitat classes (the three edge types and five Pstage categories) on murrelet populations by simulating a change in one habitat class while controlling for effects of other classes. Specifically, we simulated an immediate loss of 10,000 acres of murrelet habitat in year $t = 0$ within either (*i*) one edge class (e.g., inner edge), where Pstage classes were reduced in proportion to their availability within the focal edge class, or (*ii*) one Pstage class, where edge classes were reduced in proportion to their availability within the focal Pstage class. We created one additional scenario ("acreage") in which the simulated 10,000-acre loss in habitat occurred proportionally across all 15 edge-Pstage combinations as a basis for comparing the relative influence of habitat amount (raw acreage) vs. habitat quality (e.g., edge conditions, Pstage) on murrelet populations.

Using 10,000 acres (~5.9% of total raw acreage) ensured that proportional losses to certain habitat classes did not exceeded their availability on the landscape. For each of the 10 scenarios in the sensitivity analysis we simulated the 10,000-acre loss of habitat in year 0, ran the population model for 50 years under the *Enhancement* parameterization, and repeated 10,000 simulations using SAS 9.3. We then compared the average percent population change on DNR lands after 50 years for all scenarios and compared these changes to a baseline scenario in which no habitat loss occurred. Results of the sensitivity analysis should be interpreted as the relative (as opposed to absolute) influence of different habitat classes (raw acreage, edge, Pstage) on murrelet population growth in the region.

RESULTS

Forest Management Scenarios

Five of the eight management alternatives (C, E, F, G, and H) were projected to result in a net gain in total acres of nesting habitat on DNR lands at the end of the 50-year modeling (Figure 2a), while three of the eight management alternatives (A, B, D) were projected to result in less total acres of nesting habitat (Figure 2a). Nevertheless, all eight management alternatives were projected to result in higher nesting carrying capacity and expected nest success on DNR lands at the end of the 50-year modeling period (Figure 2b-c). Nevertheless, some alternatives differed from one another considerably with respect to all three metrics (Figure 2a-c). The most optimistic scenario for change in raw murrelet habitat was alternative F, in which habitat increased by 29% over the 50-year modeling period. In contrast, the most pessimistic scenario for change in raw habitat was alternative B, which ended with a net 13% loss in habitat after 50 years. In terms of raw habitat change, the remaining alternatives fell between B and F (Figure 2a). Similarly, differences in nesting carrying capacity (K) among the eight alternatives were bounded on the upper end by alternative F and on the lower end by alternative B. Carrying capacity increased by 147% under alternative F, while alternative B ended with a net 35%

increase in nesting carrying capacity despite a net loss in nesting habitat. Carrying capacities for the remaining alternatives always fell between B and F (Figure 2b). Mean nest success, which contributed to estimates of annual fecundity, generally increased in all scenarios over the first 30 years of the simulation then gradually decreased for the final 20 years (Figure 2c). In contrast to the eight management alternatives, the baseline scenario did not vary temporally but was structured such that the amount of raw habitat, nesting carrying capacity, and mean nest success remained constant over the 50-year modeling period.

Changes to raw habitat, nesting carrying capacity, and nest success for the exploratory variant of alternative H (H – ‘no meter’) can be found in Figure 2d-f. Alternative H – ‘no meter’ tracked alternative H closely except over the first two decades for raw habitat and carrying capacity, because alternative H – ‘no meter’ was not designed to implement the delayed harvesting strategy as in alternative H (Figure 2d-e). Nest success for alternatives H and H – ‘no meter’ was identical (Figure 2f).

Population Viability Analysis

Risk analysis, DNR population. In the *Risk* analysis, we observed considerable variation in the probability of the murrelet population on DNR lands reaching quasi-extinction thresholds across the eight management alternatives and baseline scenario (Figure 3). The probability of murrelet populations on DNR lands reaching 1/2 their initial size after 50 years ranged from 0.7964 (alternative F) to 0.9425 (alternative B). Alternatives F and G defined the lower boundary and alternative B and C defined the upper boundary of quasi-extinction probabilities for smaller thresholds: at 1/4 of initial N, quasi-extinction probability ranged from 0.3643 (alternative F) to 0.6699 (alternative B); at 1/8 of initial N, quasi-extinction probability ranged from 0.0744 (alternative G) to 0.2600 (alternative B); and at 1/16 of initial N, quasi-extinction probability ranged from 0.0039 (alternative F) to 0.0431 (alternative B). A complete list of quasi-extinction probabilities for all alternatives is provided in Table 2.

Mean female population size on DNR lands declined from 542 individuals to 196.0 (most optimistic) and 123.1 (most pessimistic) under alternatives F and B representing a 63.8% and 77.3% decline in population size, respectively, after 50 years. Mean female population size for the remaining alternatives (as well as the baseline scenario) fell between that of alternatives F and B after 50 years (Figure 4). A complete list of mean female population sizes at 10-year intervals across the 50-year modeling period is provided in Table 3.

Risk analysis, Washington population. In the *Risk* analysis, quasi-extinction probabilities for the Washington murrelet population were much more tightly clustered among the management alternatives (Figure 5). Projections of risk were presumably relatively uniform because modeled management actions were limited to DNR lands, which contained a relatively small portion (~15%) of carrying capacity for murrelets nesting in the state. The probability of the Washington murrelet population reaching 1/2 of its initial size after 50 years ranged from 0.7865 (alternative G) to 0.8159 (alternative B). For the remaining quasi-extinction thresholds, alternatives F and G generally formed the lower bound and alternatives B and C formed the upper bound. At 1/4 of initial N, quasi-extinction probability ranged from 0.3104 (alternative G) to 0.3404 (alternative B); at 1/8 of initial N, quasi-extinction probability ranged from 0.0475 (alternative G) to 0.0561 (alternative C). At 1/16 of initial N, quasi-extinction probability ranged from 0.0024 (alternative F) to 0.0041 (alternative B), although the difference between these probability estimates represents only 17 of 10,000 simulations. A complete list of quasi-extinction probabilities for all alternatives is provided in Table 2.

Mean female population size on all lands in Washington declined from 3,616 to 1,115.8 (most optimistic) and 1,064.3 (most pessimistic) under alternatives G and B representing a 69.1% and 70.6% decline in population size, respectively, after 50 years. Mean female population size among the remaining alternatives (as well as the baseline scenario) fell between that of alternatives F/G and B after 50 years (Figure 6). A complete list of mean female population sizes at 10-year intervals across the 50-year modeling period is provided in Table 3.

Enhancement analysis, DNR population. In the *Enhancement* analysis, quasi-extinction probabilities were lower on DNR lands than in the *Risk* analysis (Figure 7). The probability of murrelet populations on DNR lands reaching 1/2 their initial size after 50 years (in the absence of dispersal among land ownerships) ranged from 0.0490 (alternative F) to 0.1878 (alternative B). At 1/4 of initial N, quasi-extinction probabilities among alternatives ranged from 0.0025 (alternative F) to 0.0142 (alternative B); at 1/8 and 1/16 of initial N, quasi-extinction probability was nearly equal to zero across all alternatives (i.e. 4 or fewer of 10,000 simulations reached quasi-extinction thresholds for all alternatives). A full table of quasi-extinction probabilities for all alternatives is found in Table 2.

With the exception of the baseline scenario, in which female population size continued to decline over the 50-year modeling period, all management alternatives resulted in a murrelet population trajectory characterized by an initial decline for the first 10-20 years followed by a gradual and sustained increase through the end of the modeling period (Figure 8). Female population size on DNR lands increased from 542 individuals to 646 (most optimistic) and declined to 387.1 (most pessimistic) under alternatives F and B representing a 19% increase and

28.6% decline in population size, respectively, after 50 years. Mean female population size among the remaining alternatives fell between that of alternatives F and B after 50 years (Figure 8). A complete list of mean female population sizes at 10-year intervals across the 50-year modeling period is provided in Table 3.

Enhancement analysis, Washington population. Quasi-extinction probabilities among alternatives for the Washington murrelet population were considerably lower in the *Enhancement* than the *Risk* analysis (Figure 9). The probability of the Washington murrelet population reaching 1/2 of its initial size after 50 years ranged from 0.0548 (alternative F) to 0.0721 (alternative B). Quasi-extinction probability was nearly equal to zero for all other thresholds among all alternatives (i.e. fewer than 30 of 10,000 simulations reached quasi-extinction thresholds for all alternatives). A complete list of quasi-extinction probabilities for all alternatives is provided in Table 2.

In contrast to the *Risk* analysis, in which the Washington murrelet population followed a relatively steep and steady decline throughout the 50-year modeling period, female population size in the *Enhancement* analysis declined for 20-30 years but then remained approximately stable for the remainder of the modeling period across all alternatives (Figure 10). Female population size in the state of Washington declined from 3,616 individuals to 2,700.6 (most optimistic) and 2,452.3 (most pessimistic) individuals under alternatives F and B representing a 25.3% and 32.2% decline in population size, respectively, after 50 years. Mean female population size among the remaining alternatives fell between that of alternatives F/G and B after 50 years (Figure 10). A complete list of mean female population sizes at 10-year intervals across the 50-year modeling period is provided in Table 3.

Exploratory analyses with variant of alternative H. We evaluated the exploratory variant of alternative H under the *Risk* and *Enhancement* scenarios for DNR lands only. In the *Risk* analysis, quasi-extinction probabilities were always higher for alternative H – ‘no meter’ compared with alternative H (Figure 3, Table 2). The probability of the murrelet population on DNR lands reaching 1/2 its initial population size after 50 years was 0.8704 for alternative H – ‘no meter’ and 0.8438 for alternative H. At 1/4 of initial N, the quasi-extinction probability was again higher for alternative H – ‘no meter’ (0.5059) compared to alternative H (0.4244) and the same pattern continued at 1/8 and 1/16 of initial N (Figure 3, Table 2). Female population size declined from 542 individuals to 160.7 and 178.0 individuals under alternatives H – ‘no meter’ and H, respectively, after 50 years (Figure 4). A complete list of quasi-extinction probabilities is provided in Table 2, and mean female population sizes at 10-year intervals is provided in Table 3.

Similar to the *Risk* analysis, quasi-extinction probabilities in the *Enhancement* analysis were higher for alternative H – ‘no meter’ than for alternative H. At 1/2 of initial N, quasi-extinction probability was 0.0941 for alternative H – ‘no meter’ followed by alternative H (0.0764). This pattern persisted at 1/4 of initial N but the differences among scenarios was smaller; quasi-extinction probability was 0.0067 for alternative H – ‘no meter’ and 0.0045 for alternative H. At 1/8 and 1/16 of initial N, quasi-extinction probability was nearly zero for all three alternatives (Figure 7, Table 2). Mean female population size declined from 542 individuals to 499.7 and 510.1 individuals under alternatives H – ‘no meter’ and H, respectively, after 50 years (Figure 8, Table 3). A complete list of quasi-extinction probabilities is provided in Table 2, and mean female population sizes at 10-year intervals is provided in Table 3.

Sensitivity Analysis

Murrelet population growth was most sensitive to changes in the highest Pstage (habitat quality) classes 0.89 and 0.62; reducing the prevalence of these habitat classes on the landscape by 10,000 acres resulted in population estimates that were 18.7% and 13.4% lower than the baseline (static habitat) scenario after 50 years, respectively. Removing 10,000 acres of murrelet habitat across the 18 Pstage-edge class combinations in proportion to their availability (‘acreage’) resulted in a population estimate 10.4% lower than the baseline, which had a slightly weaker effect on murrelet population growth than removing 10,000 acres of interior forest (11.6% lower than baseline). Removing inner edge and outer edge resulted in final populations 9.1% and 8.1%, lower than the baseline scenario, respectively. Removing 10,000 acres of Pstages 0.47, 0.36, and 0.25 resulted in final populations 10.2%, 8.0%, and 5.9% lower than the baseline scenario, respectively (Figure 11).

DISCUSSION

Implications for Population Risk and Enhancement

We developed a stochastic, demographic meta-population model to compare the relative differences among alternative forest management strategies for DNR lands on the viability of marbled murrelet populations in the state of Washington. Moreover, we carried out parallel *Risk* and *Enhancement* analyses to help assess the relative manner in which proposed management actions were projected to increase population risk or the likelihood of population recovery given that it was not possible to assess both of these HCP considerations with a single analysis. Two alternatives (B and D) were projected to reduce murrelet population size compared to alternative A ("no-action"; i.e., continued management under the 1997 HCP guidelines) if murrelet populations continue to decline as a result of environmental factors unrelated to changes in nesting habitat quality and quantity (i.e., under the *Risk* analysis). Conversely, our findings suggest that all other alternatives (C, E-H) are expected to lead to larger murrelet populations than alternative A should the population continue to decline as a results of these factors. Alternative B appeared to provide less capacity for murrelet populations to increase in size than alternative A, whereas alternatives C through H led to larger murrelet populations than alternative A, under the assumption that environmental stressors likely impacting murrelets are ameliorated (i.e., in the *Enhancement* analysis). The same patterns were generally observed for quasi-extinction probabilities.

Differences in ending population size among the proposed alternatives were greater when inference was limited to the "DNR population" as opposed to the entire state of Washington, particularly when differences were considered on a percentage basis. Compared to the "no-action" alternative (A), ~1.3 times as many murrelets were expected to occur on DNR lands under alternative F after 50 years according to both *Risk* and *Enhancement* analyses (i.e., a 30% difference). While percentage differences in ending population sizes among alternatives were greater for the DNR "population" than they were for the entire Washington population, differences in the number of individuals among alternatives were more similar at the two spatial scales. For example, the difference in mean ending population size between alternative F and "no-action" (alternative A) alternatives was 44.8 for DNR lands and 20.4 individuals for the state of Washington in the *Risk* analysis. Thus, differences in abundance among the alternatives at the state level were largely the result of changes in abundance on DNR lands, which were included in state level projections of population sizes.

Comparison of Individual Alternatives

For both *Risk* and *Enhancement* analyses, alternative B consistently resulted in the lowest projected murrelet numbers after the 50-year simulation period, and generally had the highest quasi-extinction probabilities. Alternative B was the only proposed alternative that resulted in lower murrelet numbers than the "no-action" alternative (alternative A) in all analyses; both *Risk* and *Enhancement* analyses at the scale of DNR lands and the state of Washington. This finding was, to a certain extent, consistent with the fact that alternative B would include the least (576,000 acres) LTFC among all alternatives. By comparison, the "no-action" alternative (A) would involve the protection of 600,000 acres of LTFC. Compared to the "no-action" alternative (see above for details), alternative B focused only on protecting the known locations of marbled murrelet occupied sites on forested state trust lands, and was the only alternative that did not provide buffers on occupied sites. Similar to alternative B although to a lesser extent, alternative D sometimes also yielded lower projected murrelet numbers than alternative A after 50 years for both DNR lands and the state of Washington under the *Risk* analysis, but yielded slightly higher numbers than alternative A under the *Enhancement* analysis (Table 3).

In contrast, alternatives F and G consistently resulted in the highest projected murrelet numbers after the 50-year simulation period for both *Risk* and *Enhancement* analyses. At the state level, alternative F was projected to lead to an average of 47.2 and 248.3 more female murrelets than alternative B under the *Risk* and *Enhancement* scenarios, respectively; alternative G was projected to lead to an average of 51.5 and 227.1 more female murrelets than alternative B under the *Risk* and *Enhancement* scenarios, respectively. Alternatives F and G also generally had the lowest quasi-extinction probabilities. Under alternative F, 91,000 more acres (743,000 acres total) of LTFC than any other alternative (alternative G being the second most conservative, involving the protection of 643,000 acres).

In sum, alternative B posed the greatest risk to murrelet populations and alternative F (often closely followed by alternative G) provided the greatest capacity to enhance murrelet populations. Importantly, our population simulations suggested that alternatives F and B were generally the “best” and “worst”, respectively, with respect to murrelet population viability for DNR lands and the state of Washington in both the *Risk* and *Enhancement* analyses. This result is useful from a forest management perspective, because whether or not unrelated chronic environmental stressors are alleviated (i.e., the major difference in model assumptions between *Risk* and *Enhancement* analyses), alternative F is predicted to have the most positive effect on murrelet populations over the next 50 years because it provides the greatest amount of habitat and carrying capacity with the least edge effects.

Alternative H with delayed harvest suggested that harvesting over two decades as opposed to one decade (Figure 2d) ultimately translates to greater murrelet numbers and lower quasi-extinction probabilities (Tables 2 and 3). The delayed pace of harvest appears to balance with forest growth and development such that although harvesting under H results in a decline of overall habitat in the first 20 years of the simulation (Figure 2d), nesting carrying capacity remains steady and begins to increase over the same period (Figure 2e). This steady and increasing carrying capacity in the initial years of alternative H alleviates the downward pressure that projected murrelet populations experience when harvest is more rapid, resulting in greater capacity for population growth and therefore greater murrelet numbers.

Sensitivity of Marbled Murrelet Populations to Habitat Change

The sensitivity analysis suggested that murrelet populations were most sensitive to changes in the amount of higher-quality nesting habitat (Pstages 0.89 and 0.62), which exerted a stronger influence on modeled trajectories than changes in either the raw amount of nesting habitat or edge conditions (habitat configuration). Murrelet nests are typically located in large, decadent platform-bearing trees which, because of their age and economic value are relatively uncommon across the landscape and likely represent a limiting factor with respect to murrelet population densities (Burger 2001, Raphael et al. 2002). Because the highest Pstage classes represent forest stands with greater densities of platform-bearing trees suitable for nesting and presumably higher levels of murrelet use, it is therefore unsurprising that murrelet population growth appeared to be more sensitive to loss of the highest-quality habitat which, acre-for-acre, has a disproportionate influence on the population density of breeding-age murrelets. While change in habitat configuration (edge) was linked to nest success as well as nesting density in our analytical model, it nevertheless had a relatively modest influence on murrelet population growth presumably because the proportion of interior forest is considerably higher for the highest Pstages than the other categories on DNR-managed land (WDNR and USFWS 2018).

Caveats and Future Directions

Our model was parameterized with published demographic information collected for marbled murrelets from intensive field studies and structured based on a reasonable understanding and interpretation of murrelet ecology and nesting habitat needs. Moreover, the reproductive component of the model was informed by detailed assessments forest conditions in the state of Washington, and particularly on DNR lands. However, changes in climate and other environmental factors, particularly in the marine environment, that were not considered explicitly here likely also impact murrelet population dynamics and will continue to do so in the future. For example, unanticipated increases in marine stressors could further diminish murrelet populations regardless of projected increases to the amount and quality of nesting habitat. Nevertheless, the scope of this analysis was to estimate the potential and relative effect of habitat management alternatives using parameters largely under the control of land management agencies. Future areas of research could involve the development of a population model that more explicitly links risk to, for example, potential future changes in climate, oil spills, fisheries interactions, and predators.

As is always the case in PVA analyses, our model required a number of simplifying assumptions. We assumed that murrelets recruiting into the breeding population (e.g., 2-year subadults) selected nesting habitat independent of quality. Rather, individuals recruited into habitat types "proportionally" such that if, for example, three murrelets recruited into the breeding population, ~2 would do so into Pstage = 0.47 habitat and ~1 would recruit into Pstage = 0.25 habitat, even if additional nests were available in Pstage = 0.47 habitat. Second, we assumed that breeders remained in the same landownership unless they were displaced by habitat loss, and thus assumed that only nonbreeding individuals recruiting into the breeding population dispersed among landownerships. In other words, natal dispersal was permitted but, in the absence of habitat loss, breeding dispersal was not. Third, we assumed that displaced breeders (by habitat loss) could become nonbreeders for at least one year (for analytical tractability) and that displaced breeders could become breeders again if nesting habitat was available the year after they became nonbreeders. All of these aspects of murrelet breeding ecology are not well understood, and violations of associated assumptions could influence inferences regarding risk to the population.

Population viability analyses range from simple count-based approaches to more complicated spatially-explicit demographic meta-population approaches (Morris and Doak 2002). Here, we used a two-population model (DNR vs non-DNR lands) as a simplification of the complex spatial arrangement of murrelet nesting habitat in Washington given time and budgetary constraints, this simplification being agreed upon by DNR and FWS. However, the spatial arrangement of murrelet nesting habitat likely plays an important role in murrelet movement and dispersal processes throughout the state. Future efforts using spatially-explicit models could provide geographically-targeted (local) estimates of risk, prioritize stands for conservation and management, and generate more realistic insights into how changes in the spatial arrangement of nesting habitat may influence regional murrelet population viability. However, uncertainty about the landscape ecology of murrelet habitat selection and use as well as dispersal processes could obscure inference from such an effort. Finally, we note that results from PVA analyses such as ours typically constitute one of many sources of information (e.g., habitat mapping, expert opinion, etc.) that can inform species conservation and land management decisions and we recommend that they be treated as such.

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TABLES AND FIGURES

Table 1. Parameter values used is in the marbled murrelet meta-population model.

Parameter	Analysis	DNR	non-DNR	Reference/Justification
Initial (female) population size ($n_{x,L,0}$)	Both	$\sum_{i=1}^{x} n_{x,1,0} = 542$	$\sum_{i=1}^{x} n_{x,2,0} = 3{,}074$	Falxa *et al.* (2016); Lance and Pearson (2016)
Initial (female) adult non-breeders ($n_{4,L,0}$)	Both	$n_{4,1,0} = 145$	$n_{4,2,0} = 819$	40% of adult females begin as non-breeders because the population is above carrying capacity
Initial (female) adult breeders ($n_{5,L,0}$)	Both	$n_{5,1,0} = 217$	$n_{5,2,0} = 1{,}229$	
Mean 1-year old survival rate ($s_{1,L,t}$)	Both	$s_{1,1,t} = s_{2,1,t} \cdot 0.7$	$s_{1,2,t} = s_{2,2,t} \cdot 0.7$	Peery *et al.* (2006a, b)
Mean >1-year old survival rates ($s_{\geq 2,L,t}$)	*Risk*	$s_{2,1,t}, .., s_{5,1,t} = 0.87$	$s_{2,2,t}, .., s_{5,2,t} = 0.87$	Peery *et al.* (2006a, b)
	Enhancement	$s_{2,1,t}, .., s_{5,1,t} = 0.90$	$s_{2,2,t}, .., s_{5,2,t} = 0.90$	Peery *et al.* (2006a, b)
Variance in survival rates	Both	$var(s) = 0.004$	$var(s) = 0.004$	Yields coefficient of variation (CV) in simulated populations similar to process CV in population estimates from at-sea surveys
Maximum dispersal rate ($d_{L,t}$)	*Risk*, *Enhancement* (WA population	$d_{1,t} = 0.85$	$d_{2,t} = 0.15$	Equal to proportion of murrelet habitat on DNR and non-DNR lands, lower if

	only)			number of dispersers exceeds availability of nest sites in other landownership
	Enhancement (DNR population only)	$d_{1,t} = 0$	$d_{2,t} = 0$	Assumes DNR and non-DNR populations are demographically independent
Proportion of breeders (possess a nest site) that breed per year (b)	Both	$b = 0.90$	$b = 0.90$	Peery *et al.* (2004)
Mean nest success rate ($f_{L,0}$)	Both	$f_{1,0} = 0.5343$ $f_{1,\geq 1}$ varies by management alternative	$f_{2,0} = 0.5418$ $f_{2,\geq 1}$ remains constant	See Appendix A
Fecundity rate ($m_{L,t}$)	Both	$m_{1,t} = \frac{b \cdot f_{1,t}}{2}$	$m_{2,t} = \frac{b \cdot f_{2,t}}{2}$	
Variance in fecundity rate	Both	$var(m) = 0.016$	$var(m) = 0.016$	Yields coefficient of variation (CV) in simulated populations similar to process CV in population estimates from at-sea surveys
Carrying capacity (number of nests) ($K_{L,t}$), scaled	Both	$K_{1,0}$=217 $K_{1,\geq 1}$ varies by management alternative	$K_{2,0} = 1,229$ $K_{2,\geq 1}$ remains constant	See Appendix A

Table 2. Quasi-extinction probabilities for proposed forest management alternatives (A – H) under the *Risk* and *Enhancement* analyses. Note that a quasi-extinction probability of 0.0001 represents 1 out of 10,000 simulations.

Risk - DNR lands

	Fraction of Initial Population Size			
Alternative	1/16	1/8	1/4	1/2
A	0.0224	0.1745	0.5345	0.8889
B	0.0431	0.2600	0.6699	0.9425
C	0.0131	0.1206	0.4698	0.8465
D	0.0222	0.1656	0.5389	0.8895
E	0.0116	0.1234	0.4538	0.8407
F	0.0039	0.0763	0.3643	0.7964
G	0.0053	0.0744	0.3698	0.7974
H	0.0055	0.0884	0.4244	0.8438
H (no meter)	0.0180	0.1472	0.5059	0.8704
Baseline	0.0069	0.1021	0.4488	0.8940

Risk - Washington

	Fraction of Initial Population Size			
Alternative	1/16	1/8	1/4	1/2
A	0.0034	0.0541	0.3224	0.8056
B	0.0041	0.0558	0.3404	0.8159
C	0.0034	0.0485	0.3221	0.7916
D	0.0028	0.0531	0.3191	0.8082
E	0.0036	0.0514	0.3218	0.7934
F	0.0024	0.0547	0.3109	0.7903
G	0.0028	0.0475	0.3104	0.7865
H	0.0035	0.0533	0.3256	0.7963
-	-	-	-	-
Baseline	0.0027	0.0551	0.3155	0.8009

Enhancement - DNR lands

	Fraction of Initial Population Size			
Alternative	1/16	1/8	1/4	1/2
A	0	0.0002	0.0062	0.0988
B	0	0.0004	0.0142	0.1878
C	0	0.0001	0.0045	0.0711
D	0	0	0.0067	0.1051
E	0	0.0001	0.0038	0.0687
F	0	0	0.0025	0.0490
G	0	0.0001	0.0027	0.0555
H	0	0	0.0045	0.0764
H (no meter)	0	0.0002	0.0067	0.0941
Baseline	0	0	0.0069	0.1488

Enhancement - Washington

	Fraction of Initial Population Size			
Alternative	1/16	1/8	1/4	1/2
A	0	0	0.0021	0.0643
B	0	0	0.0024	0.0721
C	0	0	0.0023	0.0610
D	0	0	0.0017	0.0623
E	0	0.0001	0.0018	0.0599
F	0	0.0001	0.0010	0.0548
G	0	0	0.0026	0.0552
H	0	0	0.0024	0.0626
-	-	-	-	-
Baseline	0	0	0.0018	0.0679

Table 3. Projected mean population sizes (average of 10,000 simulations) at each 10-year interval for proposed forest management alternatives (A – H) in the *Risk* and *Enhancement* analyses.

Risk - DNR lands

	Year of Simulation					
Alternative	0	10	20	30	40	50
A	542	303.6	238.1	205.1	176.2	151.2
B	542	274.8	191.3	165.7	143.1	123.1
C	542	327.0	270.9	234.6	201.7	172.4
D	542	302.1	235.7	203.2	174.2	150.6
E	542	330.8	275.6	237.6	203.7	175.1
F	542	368.1	313.4	270.6	231.3	196.0
G	542	366.9	310.9	267.1	228.4	194.3
H	542	350.3	284.2	242.3	207.5	178.0
H (no meter)	542	312.1	252.3	217.5	186.9	160.7
Baseline	542	347.9	274.1	226.3	188.4	158.4

Risk - Washington

	Year of Simulation					
Alternative	0	10	20	30	40	50
A	3616	2316.2	1836.1	1524.7	1285.4	1091.1
B	3616	2281.3	1789.9	1491.7	1255.6	1064.3
C	3616	2339.5	1866.3	1558.2	1313.8	1112.0
D	3616	2313.9	1833.8	1520.9	1277.5	1090.0
E	3616	2340.0	1869.6	1554.6	1307.8	1114.0
F	3616	2356.6	1879.5	1569.0	1319.6	1111.5
G	3616	2362.6	1887.2	1569.0	1319.6	1115.8
H	3616	2348.1	1870.9	1550.8	1302.7	1105.3
-	-	-	-	-	-	-
Baseline	3616	2336.2	1852.8	1541.6	1294.1	1097.1

Enhancement - DNR lands

	Year of Simulation					
Alternative	0	10	20	30	40	50
A	542	406.0	373.1	392.0	429.1	473.8
B	542	378.2	314.1	320.9	350.2	387.1
C	542	427.2	412.8	440.5	483.5	533.3
D	542	403.1	368.6	392.0	432.0	478.7
E	542	429.5	419.7	446.4	492.6	546.6
F	542	453.2	463.9	507.5	569.2	646.0
G	542	450.2	455.4	493.4	543.4	599.7
H	542	431.8	406.2	423.6	462.4	510.1
H (no meter)	542	414.5	387.6	413.1	451.4	499.7
Baseline	542	431.2	391.2	374.0	364.9	358.9

Enhancement - Washington

	Year of Simulation					
Alternative	0	10	20	30	40	50
A	3616	2863.4	2609.1	2527.8	2517.3	2537.5
B	3616	2844.1	2558.0	2470.2	2444.8	2452.3
C	3616	2892.2	2663.2	2578.8	2569.4	2592.4
D	3616	2863.3	2616.1	2541.7	2529.0	2547.8
E	3616	2887.6	2667.7	2596.5	2587.3	2620.1
F	3616	2906.1	2696.8	2640.6	2652.9	2700.6
G	3616	2919.1	2707.3	2636.5	2634.3	2679.4
H	3616	2880.3	2650.1	2567.0	2552.2	2573.6
-	-	-	-	-	-	-
Baseline	3616	2879.4	2629.0	2519.7	2461.8	2425.5

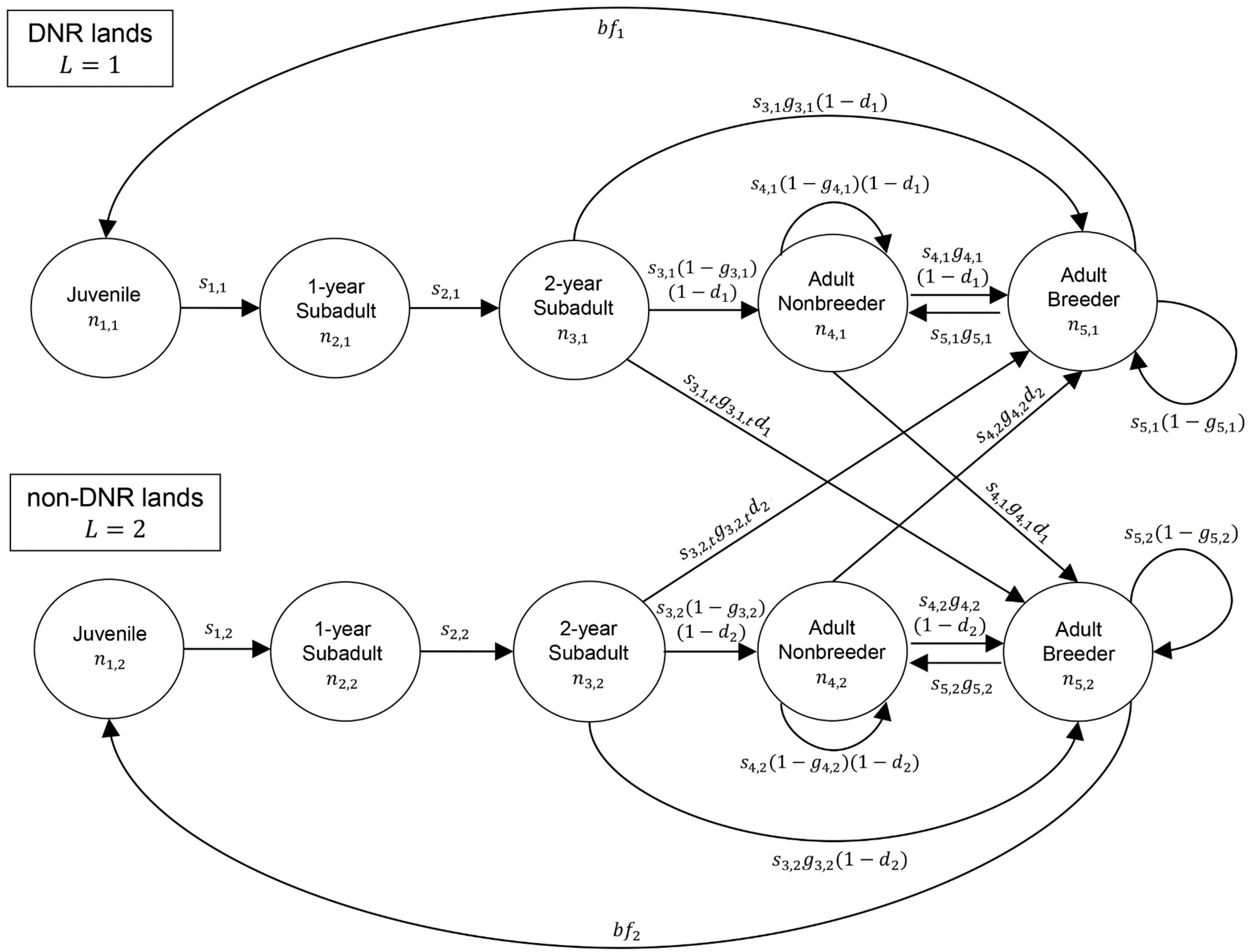


Figure 1. Life-cycle diagram for the demographic meta-population model used to evaluate the potential effects of Washington DNR's

management alternatives on marbled murrelets. $n_{x,L}$ represents the number of female murrelets; $s_{x,L}$ represents the survival probability; $g_{x,L}$ represents the transition probability; d_L represents the dispersal probability; b represents the breeding probability; f_L represents nest success rate; the subscript x = 1,2,…,5 represents stage classes juvenile, 1-year subadult, 2-year subadult, adult nonbreeder, and adult breeder, respectively; the subscript L = 1, 2 represents DNR and non-DNR lands, respectively. Note that time t was not included in the diagram for simplicity.

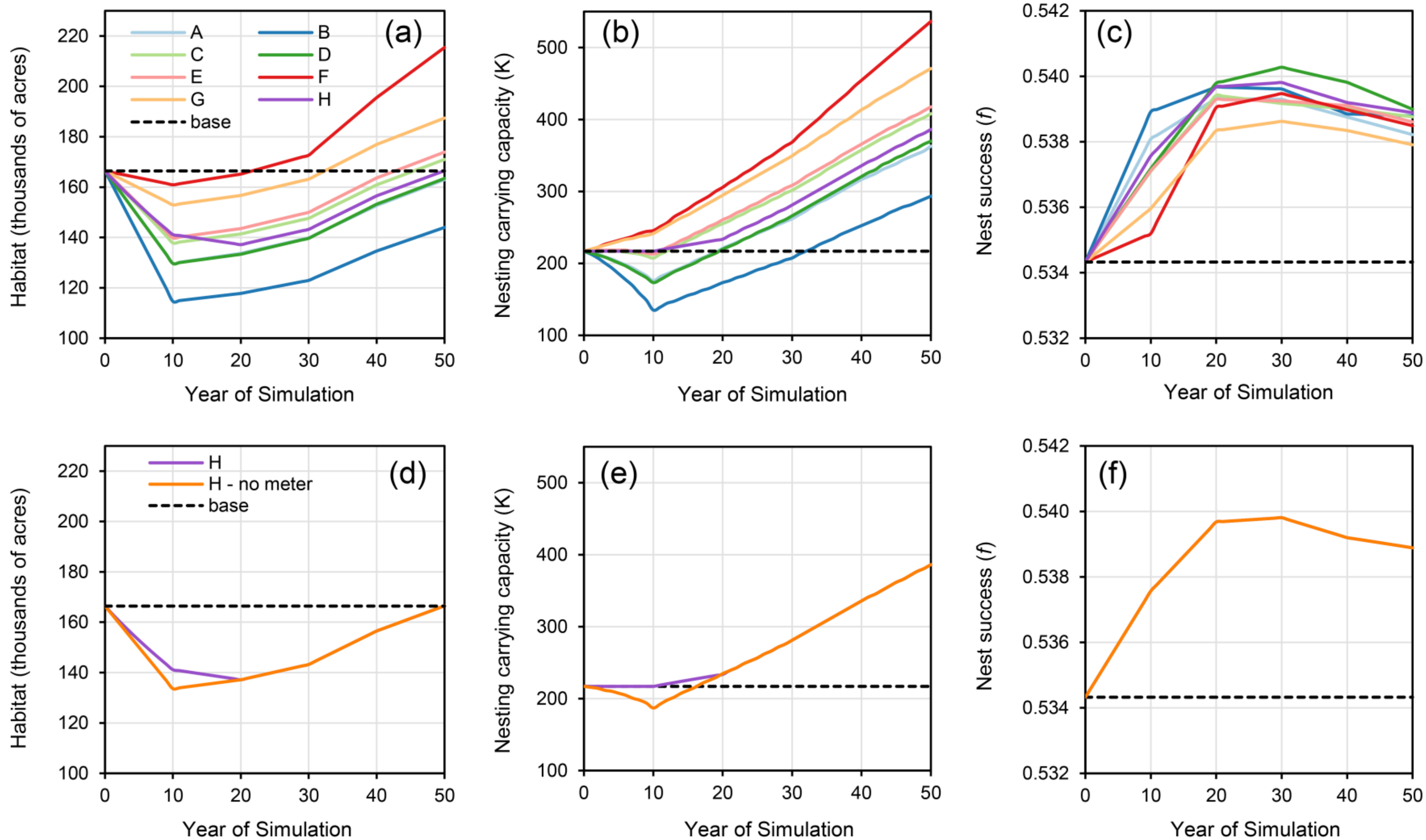


Figure 2. Forest management alternatives proposed by the Washington DNR and the U.S. Fish and Wildlife Service. The raw amount of nesting habitat, carrying capacity, and nest success on DNR-managed lands for each of the primary alternatives (A – H) over the modeling period are presented in panels a – c, respectively. Habitat "strings" are not included in these estimates. The same measures

for the exploratory alternative (H – ‘M’) is shown in panels d – f, and includes alternative H for the purposes of comparison.

Note: The lines showing nest success for alternatives H and H-M are on top of one another.

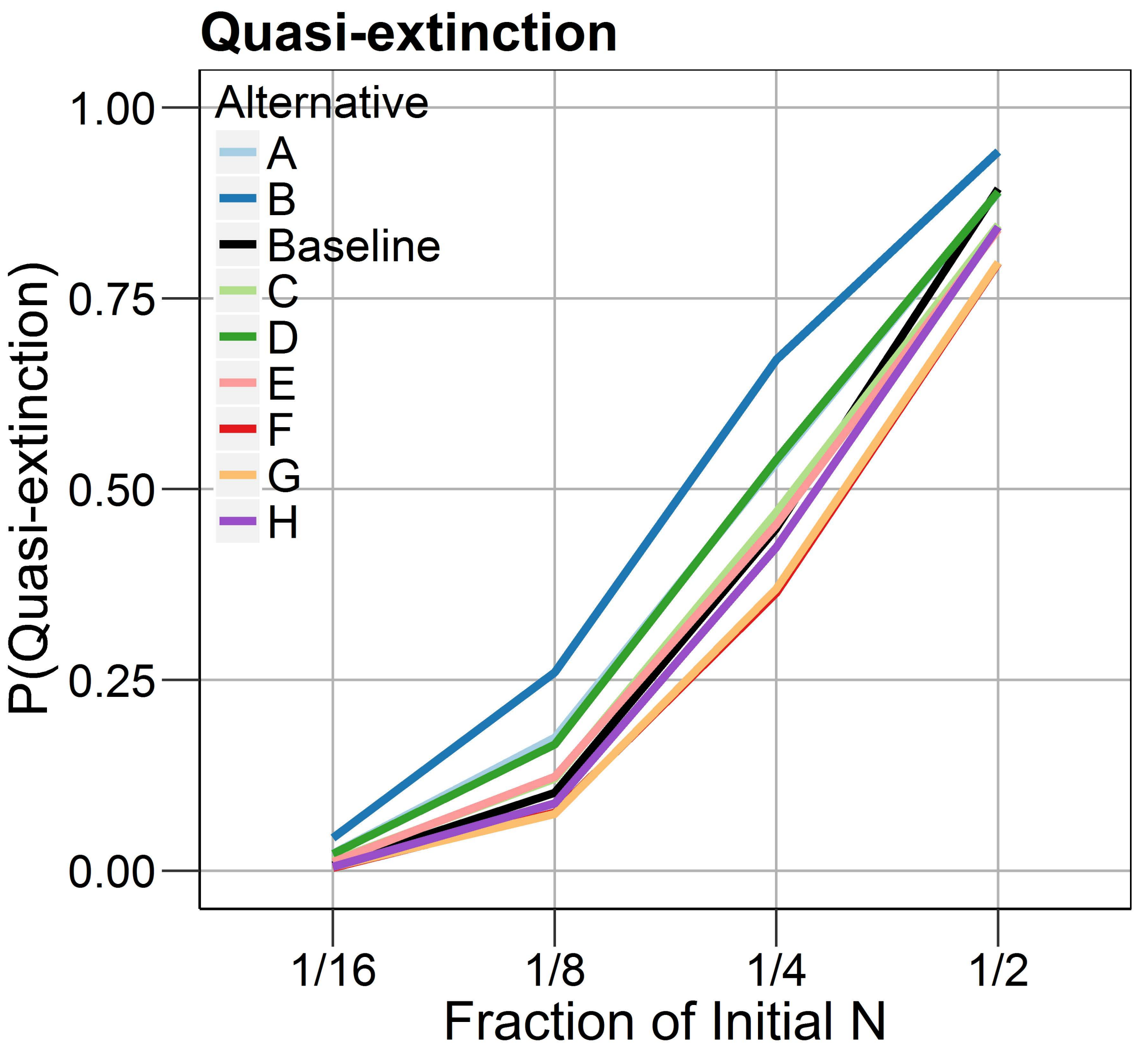


Figure 3. *Risk* analysis – DNR lands. Quasi-extinction probabilities (proportion of 10,000 simulations that reached a specified fraction of initial population size) for the proposed management alternatives.

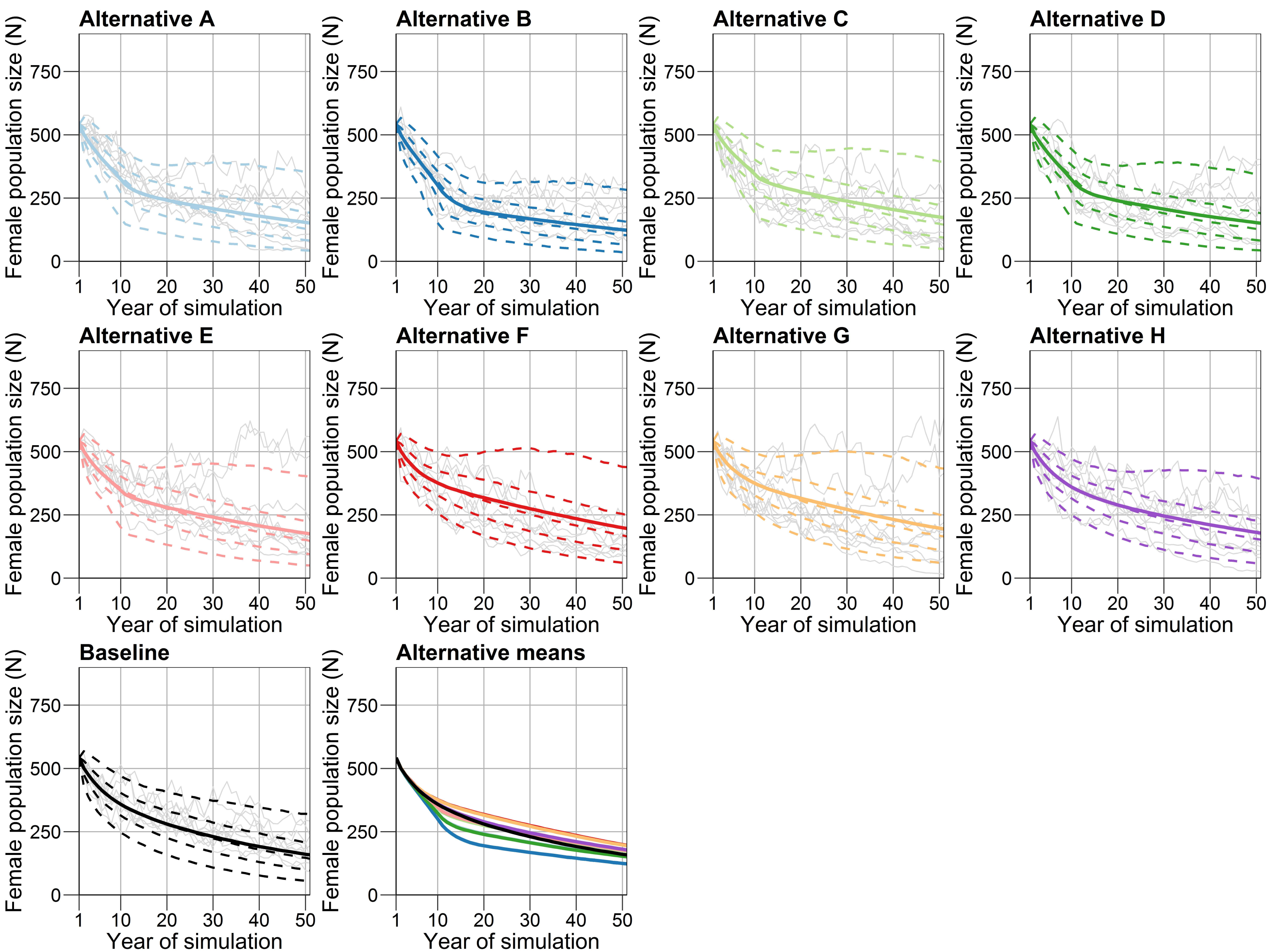

Alternative A
Alternative B
Alternative C
Alternative D
Alternative E
Alternative F
Alternative G
Alternative H
Baseline
Alternative means
Female population size (N)
Year of simulation
0
250
500
750
1
10
20
30
40
50

Figure 4. *Risk* analysis – DNR lands. Projected murrelet population sizes as a function of proposed management alternatives. In each panel the solid colored line represents the mean annual population size averaged over 10,000 simulations, the dashed colored lines represent the 5%, 25%, 50% (median), 75%, and 95% quantiles, and the grey lines represent a random subsample (n = 10) of individual simulation outcomes. The bottom-right panel ("Alternative means") plots the mean from each alternative on a single graph for the purposes of comparison.

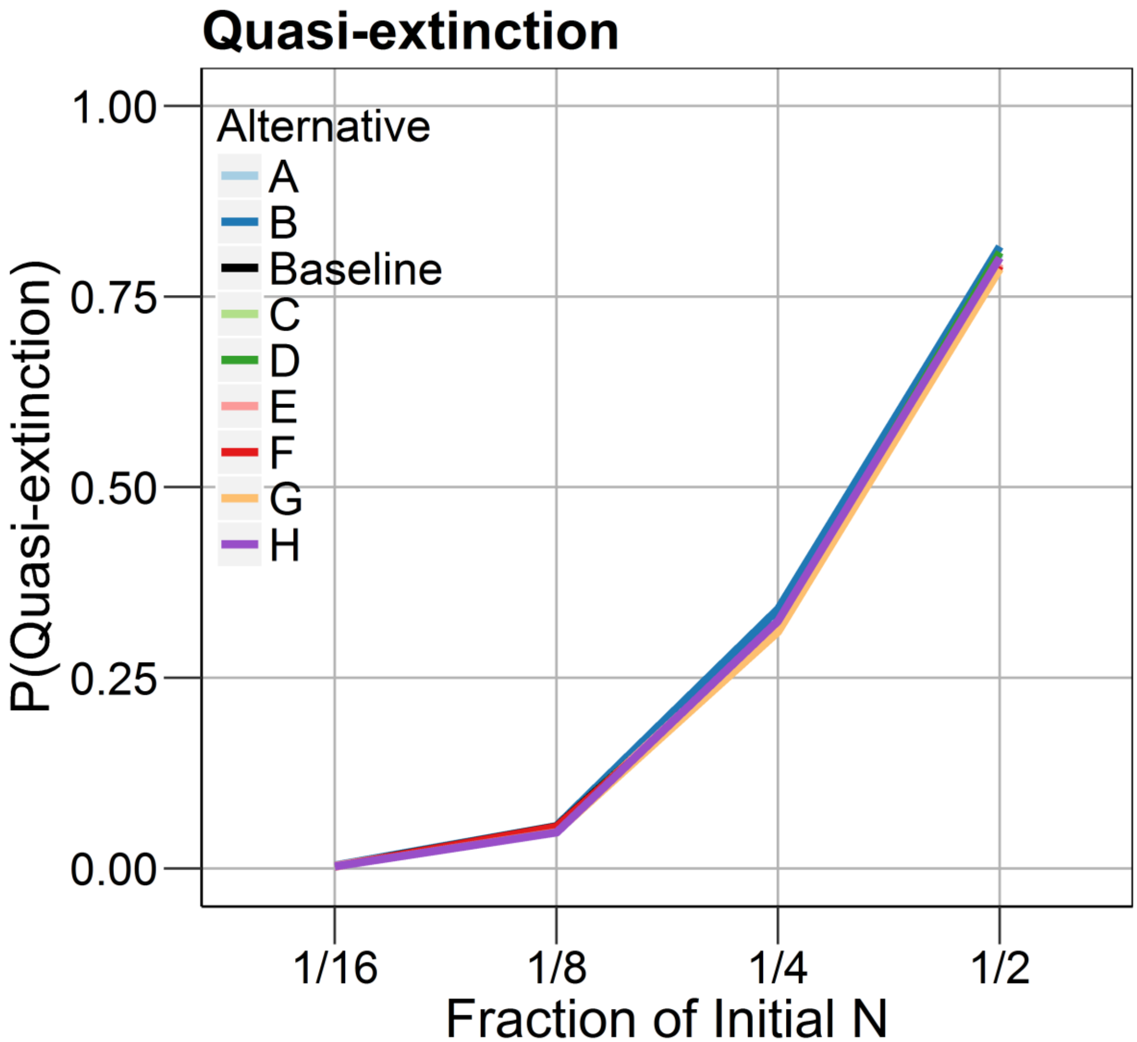
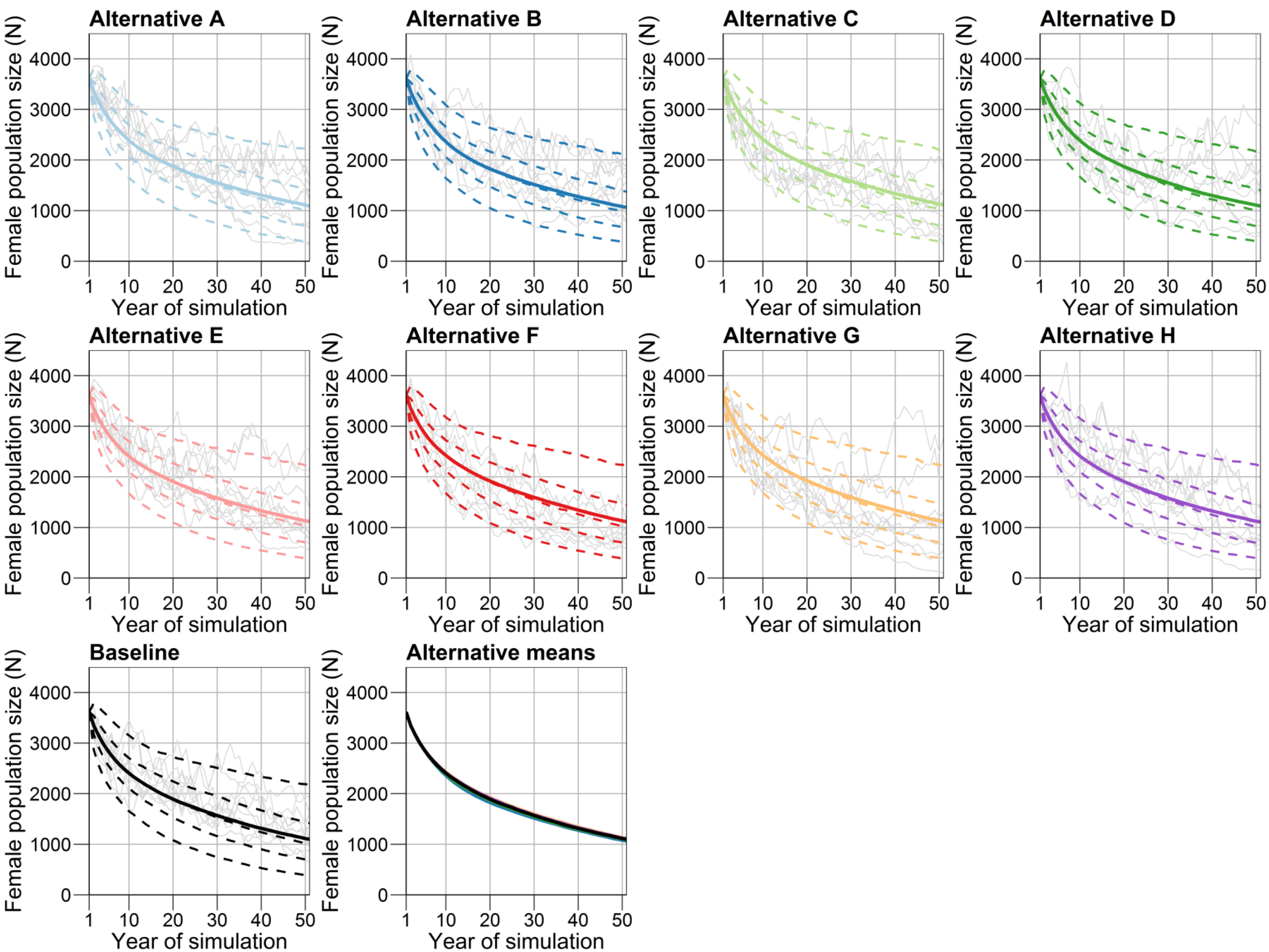


Figure 5. *Risk* analysis – Washington. Quasi-extinction probabilities (proportion of 10,000 simulations that reached a specified fraction of initial population size) for the proposed management alternatives.



Alternative A
Alternative B
Alternative C
Alternative D
Alternative E
Alternative F
Alternative G
Alternative H
Baseline
Alternative means
Female population size (N)
Year of simulation
0
1000
2000
3000
4000
1
10
20
30
40
50

Figure 6. *Risk* analysis – Washington. Projected murrelet population sizes as a function of proposed management alternatives. In each panel the solid colored line represents the mean annual population size averaged over 10,000 simulations, the dashed colored lines represent the 5%, 25%, 50% (median), 75%, and 95% quantiles, and the grey lines represent a random subsample (n = 10) of individual simulation outcomes. The bottom-right panel ("Alternative means") plots the mean from each alternative on a single graph for the purposes of comparison.

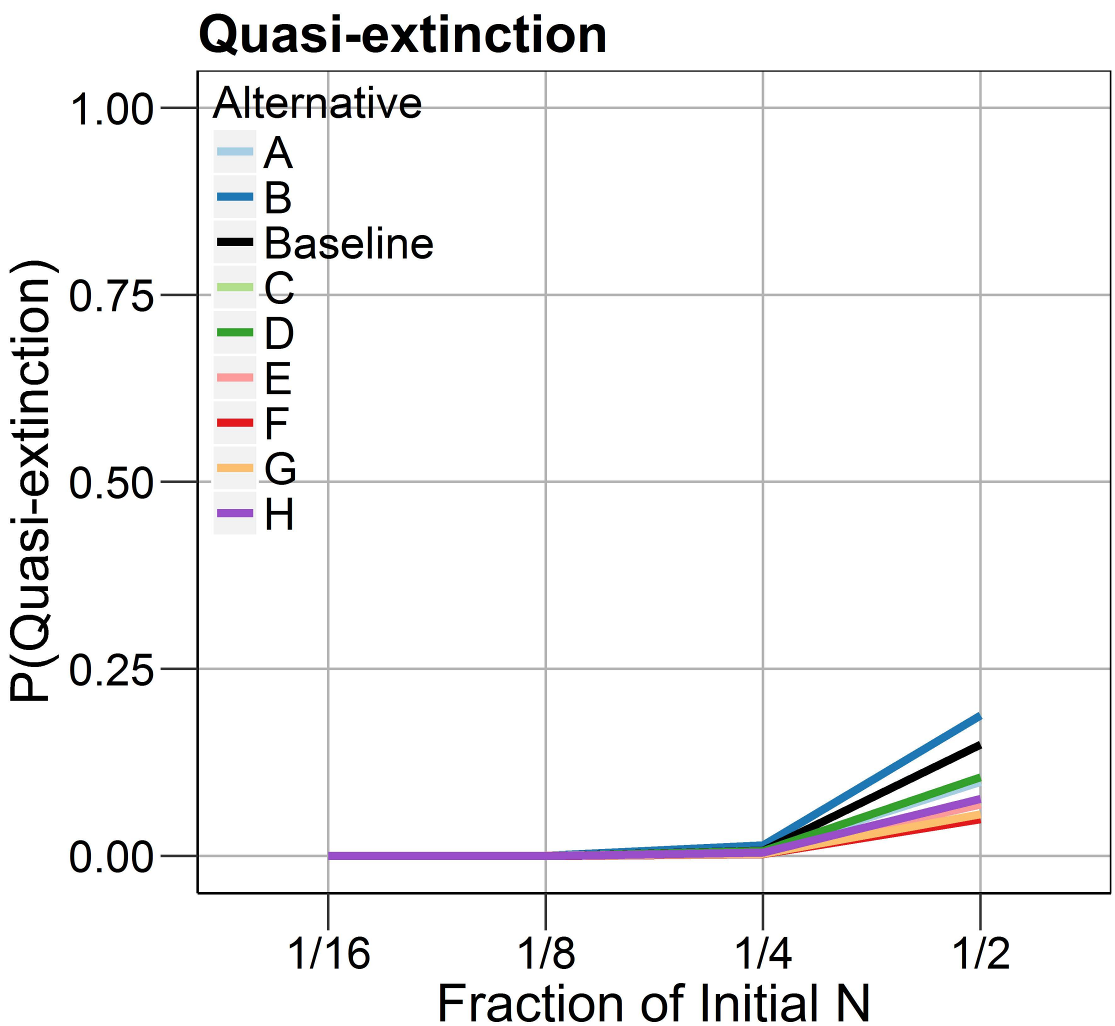


Figure 7. *Enhancement* analysis – DNR lands. Quasi-extinction probabilities (proportion of 10,000 simulations that reached a specified fraction of initial population size) for the proposed management alternatives.

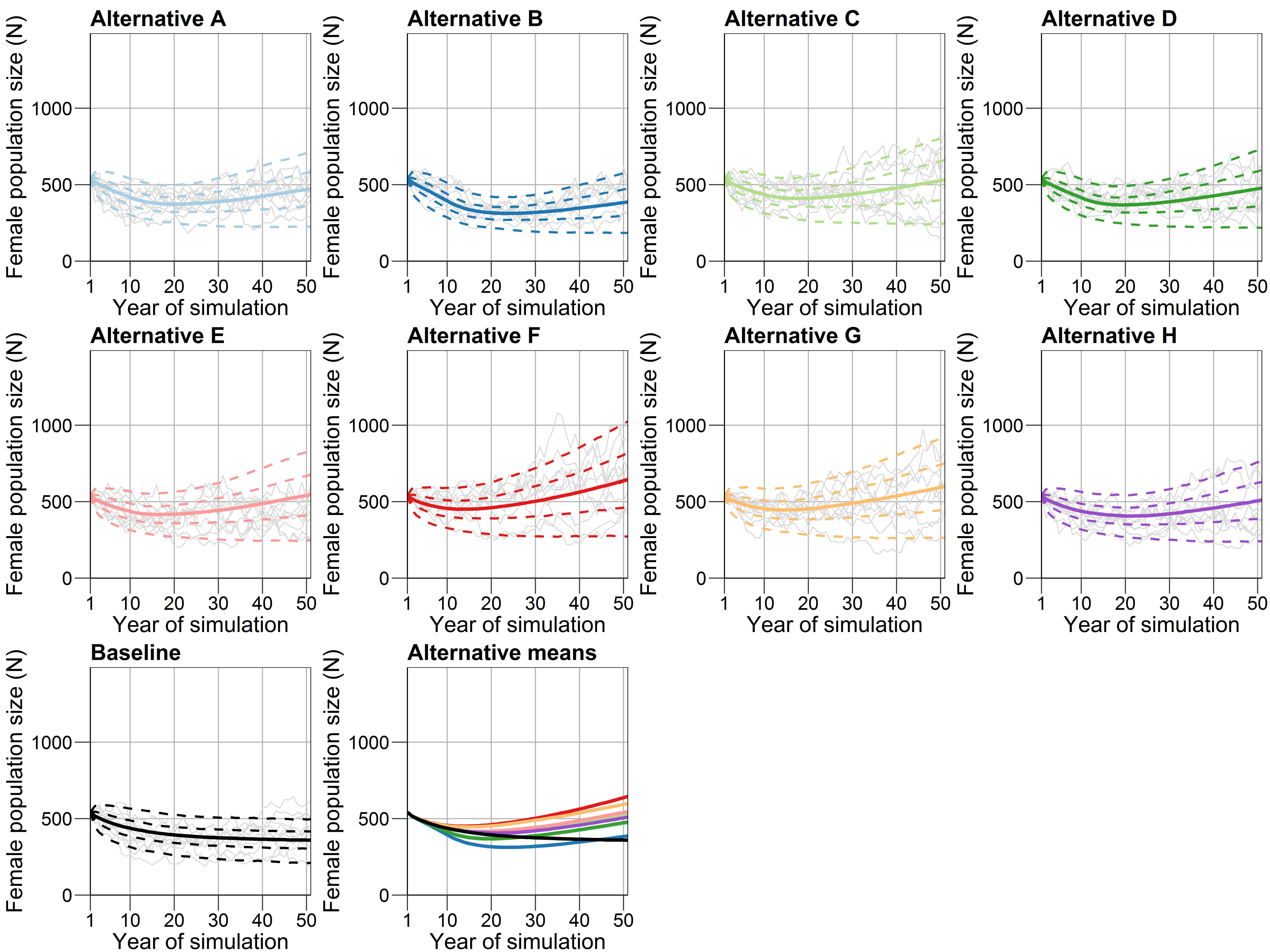

Alternative A
Alternative B
Alternative C
Alternative D
Alternative E
Alternative F
Alternative G
Alternative H
Baseline
Alternative means
Female population size (N)
Year of simulation
0
500
1000
1
10
20
30
40
50

Figure 8. *Enhancement* analysis – DNR lands. Projected murrelet population sizes as a function of proposed management alternatives. In each panel the solid colored line represents the mean annual population size averaged over 10,000 simulations, the dashed colored lines represent the 5%, 25%, 50% (median), 75%, and 95% quantiles, and the grey lines represent a random subsample (n = 10) of individual simulation outcomes. The bottom-right panel ("Alternative means") plots the mean from each alternative on a single graph for the purposes of comparison. Note that in this set of graphs the line representing the 50% quantile (median) is not visible because it is obscured by the line representing the mean.

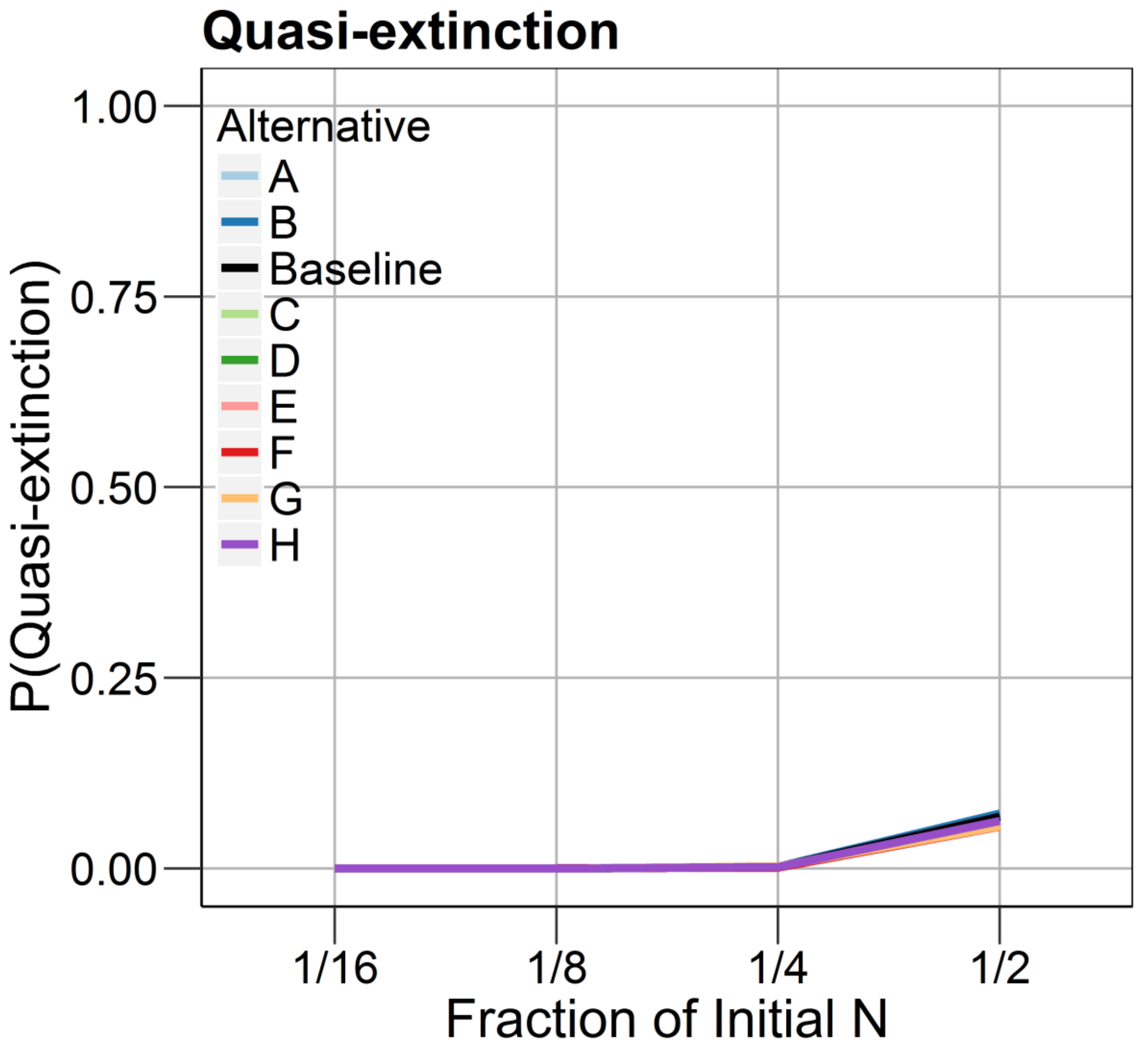
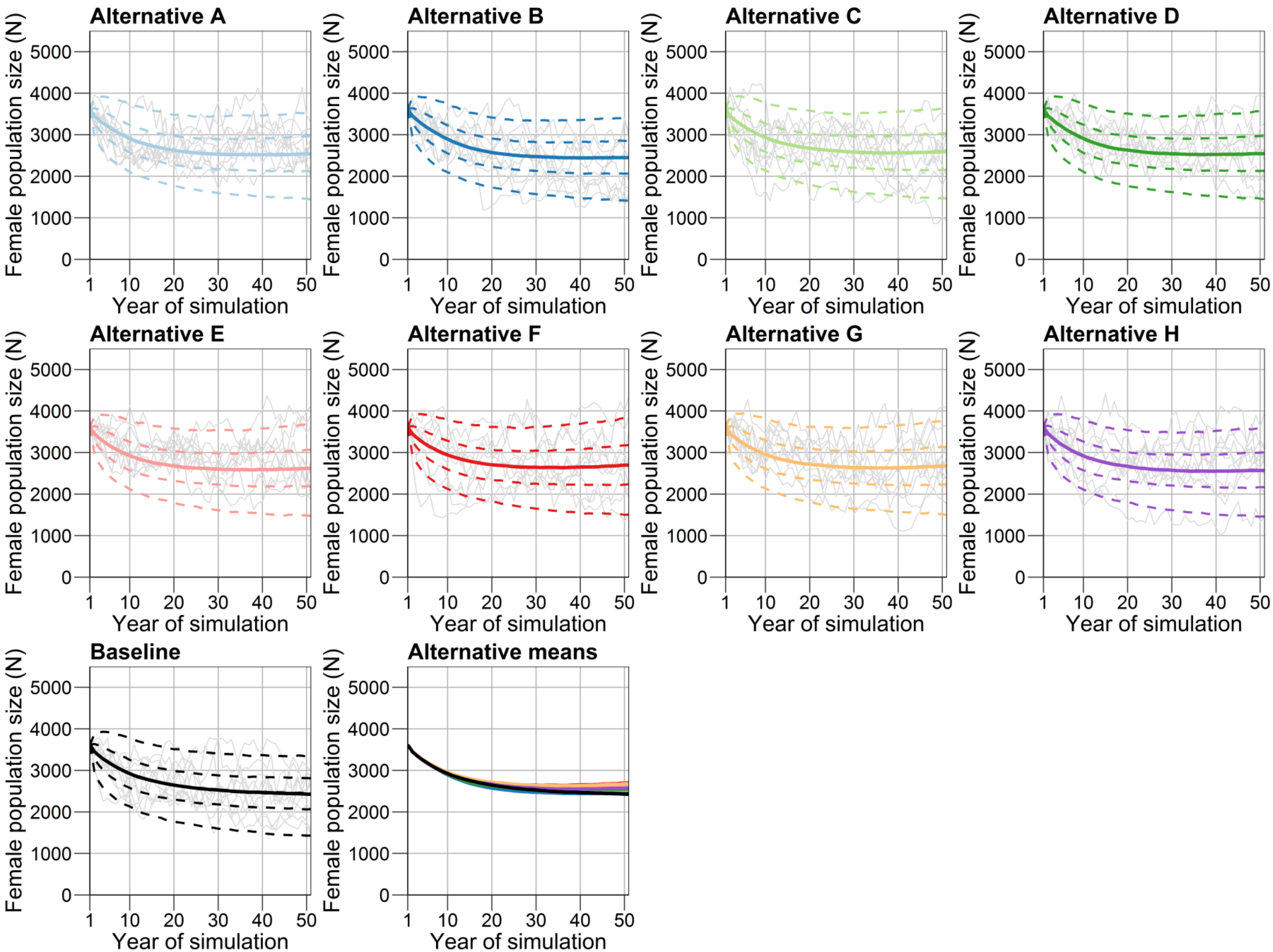


Figure 9. *Enhancement* analysis – Washington. Quasi-extinction probabilities (proportion of 10,000 simulations that reached a specified fraction of initial population size) for the proposed management alternatives.



Alternative A
Alternative B
Alternative C
Alternative D
Alternative E
Alternative F
Alternative G
Alternative H
Baseline
Alternative means
Female population size (N)
Year of simulation
0
1000
2000
3000
4000
5000
1
10
20
30
40
50

Figure 10. *Enhancement* analysis – Washington. Projected murrelet population sizes as a function of proposed management alternatives. In each panel the solid colored line represents the mean annual population size averaged over 10,000 simulations, the dashed colored lines represent the 5%, 25%, 50% (median), 75%, and 95% quantiles, and the grey lines represent a random subsample (n = 10) of individual simulation outcomes. The bottom-right panel ("Alternative means") plots the mean from each alternative on a single graph for the purposes of comparison.

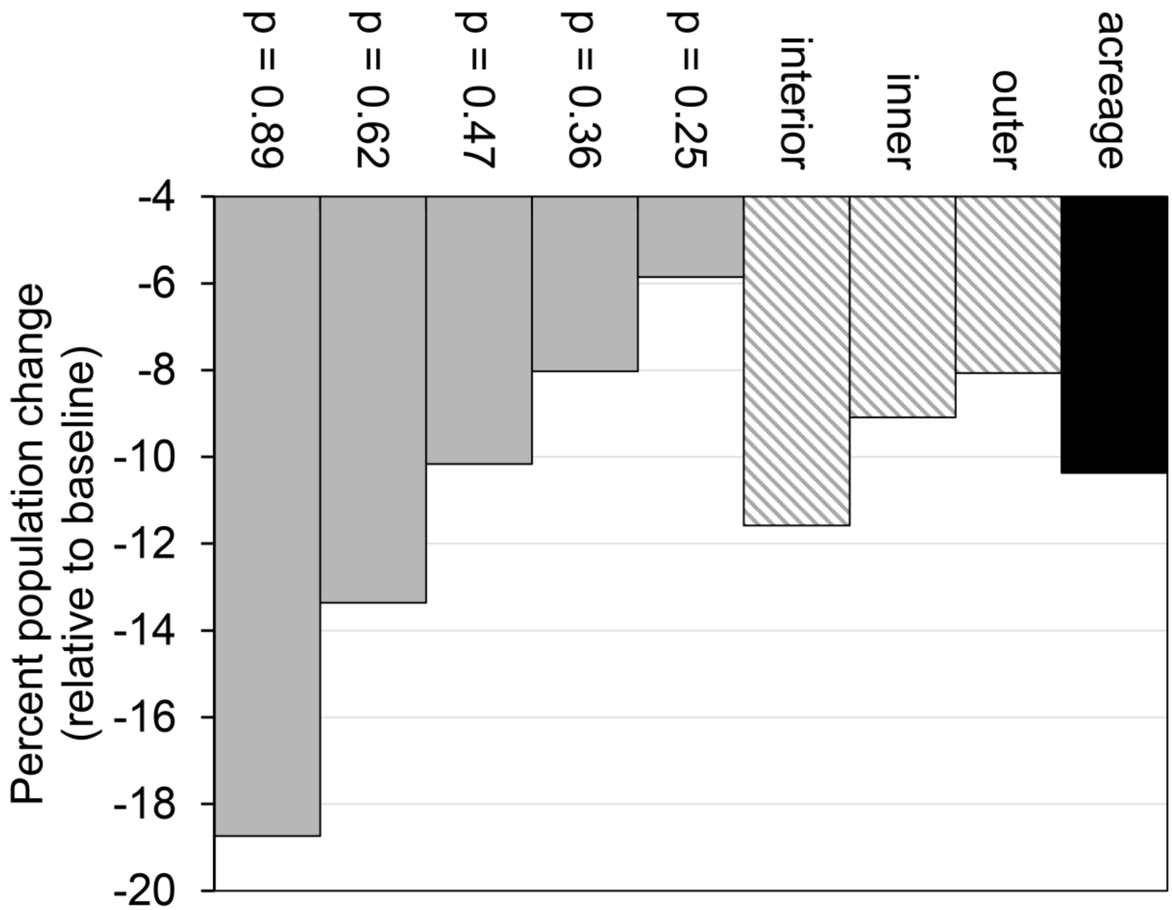


Figure 15. Sensitivity analysis. Grey solid bars represent habitat quality (Pstage), grey hatch-marked bars represent habitat configuration (edge conditions), and the black bar represents habitat amount (raw acreage).

APPENDIX A

Nest Density – Based on the assumptions that a threshold acreage of habitat is required to provide one nest site and that nesting habitat is limited so that there is just enough for the current statewide population, i.e., the population is at the carrying capacity, *K*, of its forest habitat. WA state habitat estimates are from Raphael et al. (2016) and the murrelet population is estimated as the average WA at-sea population over a 5 year monitoring period, 2011-2015. Due to reduced-sampling efforts implemented in 2014, state-scale estimates for Washington are not currently available for the 2016 or 2017 monitoring years (Lynch et al. 2016). Habitat quality, and consequently the availability of potential nest sites, is assumed to be influenced by stand condition, edge effects including lack of habitat capability in strings, and geography (see below). Adjusted acreages for non-DNR land are based on Science Team (Raphael et al. 2008) assumptions for habitat quality and accessory assumptions for edge conditions and strings (i.e., assume federal habitat consists of half as much edge and strings while private habitat consists of 50% more edge and strings than DNR-managed land). Adjusted acreages for DNR land are based on assumptions regarding the influence of stand development, edge effects, and geography on habitat quality (see below) applied to estimated habitat acreage (Raphael et al. 2016). Nest density, *D*, is estimated as the total number of murrelets in WA divided by the total adjusted habitat acreage, *A*.

Raw Habitat (DNR) – Acreage of habitat (*Pstage*>0) symbolized as *H*, based on interpretation and projection of DNR's spatially-explicit forest inventory. This estimate of current habitat (*Pstage*>0), 211,700 acres, differs slightly from that of Raphael et al. (2016) which was used to estimate nest density, 187,100 acres.

Adjustment for Habitat Quality (DNR) – This incorporates three influences on habitat quality as it relates to function in providing nesting opportunities and *K*: stand condition, edge effects, and geography. DNR's spatially-explicit forest inventory summarizes acreage (*H*), composition, and structure for stands, contiguous forest patches with sufficiently uniform composition and structure to be distinguishable units. Each stand has a current and projected future *Pstage* value (0, 0.25, 0.36, 0.47, 0.62, 0.89) which reflects habitat quality, thus its capacity to provide nest sites as *H* * *Pstage*. Edge effects, *E*, are influenced by two factors, distance from edge and edge type as summarized in the table below. Edge type and distance were estimated with spatial analyses of DNR forest inventory and the proposed conservation alternatives. Geographic influence, *G*, was incorporated by mapping habitat over 5 km from the nearest occupied murrelet site where the diminished attractiveness and/or availability of nest sites was assumed to have a further effect, 0.25, on habitat quality at these isolated habitat patches. Less than 5% of DNR-managed habitat, *H*, is so isolated, thus *G* = 1 for the large majority of habitat.

		Interior (*t*)	Inner Edge (r)	Outer Edge(*o*)	String
Edge Type	None (*n*)	1	1	1	0
	Soft (*s*)	1	0.8	0.6	0
	Hard (*h*)	1	.585	.17	0

Stands of current and projected future habitat (*Pstage*>0) were spatially partitioned by multiple factors important to DNR forest management including edge distance and geography (approximately 1,000,000 partitions varying by time-step and alternative), so that each partition, *i*, had an unique acreage H_i, and was in one of twenty-four *Pstage*/Edge-distance categories. Habitat was configured either in small, often fairly linear fragments called *strings* that contained no interior forest, or in larger blocks that contained habitat in outer (*o*) and inner (*n*) edges as well as in interior forest (*t*), >100 meters from edge. Edge effects were assumed to negate the value of habitat in strings. Depending on alternative, 13% - 24% of habitat was in strings. Edge effects on inner and outer edge habitat was estimated with spatial methods based on the location of p-stage, and estimates of forest growth in LTFC based on site index values from DNR's forest inventory. Edges outside of LTFC were assumed to be equal to current proportions of edge types due to the balance of growth and harvest across the land base. Thus, projected future edge effects to inner and outer edge forests varied by alternative over the 50 year modeling period.

Six of the eighteen, non-string *Pstage*/Edge-distance categories are interior (*t*) and not subject to edge effects. The habitat quality adjustments described above were applied to all *j* spatial partitions within the interior categories and estimate the "functional capability" of murrelet habitat over 100 meters from potential edge as the sum of adjusted habitat acreage:

$$A_t = \sum_{i=1}^{j} H_i * Pstage_i * G_i * E_t$$

where $E_t = 1$. The adjusted habitat acreage within inner and outer edge categories are calculated as:

$$A_r = \sum_{i=1}^{j} H_i * Pstage_i * G_i * ((E_{nr} * p_n) + (E_{sr} * p_s) + (E_{hr} * p_h))$$

and

$$A_o = \sum_{i=1}^{j} H_i * Pstage_i * G_i * ((E_{no} * p_n) + (E_{so} * p_s) + (E_{ho} * p_h)),$$

respectively. The sum of adjusted acreages in interior and the two edge categories estimates A_{DNR},

$$A_{DNR} = A_t + A_r + A_o.$$

K (DNR) – The estimated number of nest sites on DNR-managed land, calculated as $K_{DNR} = D * A_{DNR} * 0.5$ to reflect a population that is half female.

Nest Success (DNR) – Based on the assumption that edge effects are a primary influence on nest success, f. High nest success, f_{high} is assumed to be 0.55 and low success, f_{low}, 0.38 (McShane et al. 2004), with intermediate success, f_{int}, halfway between. Edge effects are influenced by two factors, distance from edge and edge type as summarized in the table below (Malt and Lank 2009). Edge type and distance from edge were estimated with spatial analysis of DNR forest inventory.

		Interior	Inner Edge	Outer
Edge Type	None (n)	0.55	0.55	0.55
	Soft (s)	0.55	0.55	0.55
	Hard (h)	0.55	0.465	0.38

Similar to adjustments for habitat quality, nest success was estimated by a combination of spatial and non-spatial analyses. Seven of the nine Edge-distance/Edge-type categories are interior or influenced by no or soft edge and are not subject to edge effects. Their influence on nest success, f, was estimated for all j spatial partitions within those categories as

$$f_{t,n,s} = \sum_{i=1}^{j} H_i * f_{high}$$

The influence of inner and outer hard edges on nest success was estimated as

$$f_{hr} = \sum_{i=1}^{j} H_i * f_{int}$$

and

$$f_{ho} = \sum_{i=1}^{j} H_i * f_{low}$$

thus

$$f_{DNR} = f_{t,n,s} + f_{hr} + f_{ho}$$

Raw Habitat (Other) – Estimates from Raphael et al. (2016).

Adjustment Factor (Other) – Based on the same logic and edge effects described for the DNR adjustment factor but using Science Team (Raphael et al. 2008) assumptions for habitat quality and the assumptions for edge conditions and strings summarized above, i.e., federal habitat consists of half as much edge and strings while private habitat consists of 50% more edge and strings than DNR-managed land.

K (Other) – The estimated number of nest sites on federal and other non-federal land, calculated as described above.

Nest Success (Other) – Estimated as above, based on the assumptions about edge on non-DNR lands (federal habitat consists of half as much edge while private habitat consists of 50% more edge than DNR-managed land).

Additional references

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P-stage Focus Paper

Estimating the Location and Quality of Marbled Murrelet Habitat

Focus Paper #3

This focus paper was part of a series presented to the Board of Natural Resources in October and November 2015 to inform development of the marbled murrelet long-term conservation strategy alternatives. The purpose of this paper is to describe how DNR and USFWS identify and classify marbled murrelet habitat for purposes of developing the long-term conservation strategy.

■ Identifying Marbled Murrelet Nesting Habitat

Marbled murrelets were proposed for listing under the Endangered Species Act in part because their nesting habitat in older, complex-structured forests was thought to be so diminished by timber harvest that nesting opportunities were limiting the population (USFWS 1992). Contemporary research continues to support the importance of both *quantity* and *quality* of nesting habitat to murrelet distribution and abundance (for example, Raphael and others 2015). For the development of a long-term conservation strategy, DNR and USFWS require a credible method, a “habitat model,” to identify the current and potential future location and quality of marbled murrelet habitat across DNR-managed lands. Specific objectives for a habitat model were that it be:

- Consistent with contemporary scientific findings on the relationships of murrelet nesting biology with forest characteristics,
- Applicable to DNR-managed lands within the analysis area,

- No more complex than necessary,
- Of a geographic scale and resolution consistent with DNR forest inventory,
- Appropriately consistent with independent habitat assessments on DNR-managed land, and
- Consistent with data and models for forest structure and composition, growth, habitat quality and development.

Using Forest Inventory Data

Marbled murrelet nesting habitat key components:

- Nest platforms
- Flight access to platforms
- Security from predators
- Located within 55 miles of marine habitat

Murrelet nesting habitat is widely considered to have four components that interact to attract nesting murrelets and support their successful nesting: potential nest sites (platforms), flight access to the platforms, nest site- and neighborhood-level security from nest predators, and location within commuting distance of marine habitat (considered to be 55 miles inland). The presence and abundance of platforms and canopy complexity that enables flight access and provides site-level security are characteristics of forest stands[1] that can be evaluated using DNR's comprehensive forest inventory. This inventory includes data for stands across all DNR-managed forest lands. A variety of inventory measurements of live and dead trees, other plants, and site conditions are used to provide stand-level estimates of timber volume and value, growth potential, habitat potential, and other important attributes. These forest inventory data also provide the basis for identifying the location and quality of current and future murrelet habitat according to methods agreed upon by DNR and USFWS and described here. The resulting estimates are essential for purposes of conservation planning. Forest stands with high value as nesting habitat, or with the potential to develop nesting habitat characteristics within the tenure of the 1997 HCP, can be identified and incorporated in conservation strategies.[2] Likewise, these estimates can provide an objective basis for evaluating and adjusting forest management to arrive at a conservation strategy that meets the mandates of both DNR and USFWS.

What Habitat Classification Models are Available?

Since the marbled murrelet was listed under the Endangered Species Act in 1992, USFWS and DNR have used various methods to define and identify murrelet habitat.

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[1] A forest stand is a contiguous group of trees sufficiently uniform to be a distinguishable unit. Definition provided by Society of American Foresters. 1998. Dictionary of Forestry. http://dictionaryofforestry.org/dict/term/stand

[2] Refer to Appendix G, "LTFC Focus Paper,"for a description of how the strategy delineates these areas; refer to Appendix H, "Potential Impacts and Mitigation Focus Paper," for a discussion of activities that may impact the murrelet.

HABITAT MODELING UNDER THE HCP INTERIM STRATEGY

The 1997 HCP includes an interim strategy that directs DNR to follow a stepwise process of increasingly focused identification and protection of habitat. The interim strategy has led to deferrals of harvest of the most important habitat (and some harvest deferrals in less important habitat) while DNR continues to gather knowledge about how and where marbled murrelets use habitat on DNR-managed lands. (Refer to Appendix D, "Occupied Sites Focus," for a detailed description of the interim strategy.) The first step of the interim strategy is to identify "suitable habitat blocks," which requires intensive fieldwork and has therefore mostly been applied to screening site-specific timber harvest proposals, rather than comprehensive habitat inventory and conservation planning. This first step was followed by the development of habitat relationship models, planning-unit specific statistical models that used a suite of of stand and neighborhood-level characteristics to predict the likelihood of murrelet use (occupancy) based on 1997 HCP-directed murrelet research in a sample of 54 forest stands in each planning unit (Prenzlow Escene 1999).[3] Based on these models, habitat mapping ("reclassification") was done across DNR-managed lands in four planning units, and audio-visual murrelet surveys were conducted in that habitat to determine the extent of marbled murrelet occupancy and further refine implementation of the interim strategy. Habitat relationship modeling was not successful in the North and South Puget HCP planning units; the interim strategy continues to use suitable habitat blocks to identify and protect habitat in those units.

NORTHWEST FOREST PLAN MODELING

Other comprehensive, region-wide habitat models have been developed for habitat inventory and monitoring to support the federal Northwest Forest Plan (1994). The "*Biomapper*" model was published in the ten-year review of the plan (Raphael 2006) and was used by the Science Team (Raphael and others 2008) in their analysis of murrelet conservation opportunities. Further work by the NWFP team led to updates using a different habitat modeling technique, "*Maxent*," the results of which were published in the fifteen-year and 20-year reviews of the Northwest Forest Plan (Raphael and others 2011; Falxa and Raphael 2015). The 20-year review provides the best available landscape scale estimate of the amount and location of murrelet habitat across all lands in Washington. It is not specific to DNR-managed lands.

SCIENCE TEAM MODELING

In 2004, DNR convened a team of scientists to assess the state of knowledge on murrelets and their habitat on DNR-managed lands in order to provide recommendations on conservation opportunities. This "Science Team" published a report that included a habitat model that used DNR's forest inventory to predict current and future locations and quality of murrelet habitat (Raphael and others 2008).

Why was the Science Team's Classification Model Selected to Estimate Marbled Murrelet Habitat for the Long-term Conservation Strategy?

For the long-term conservation strategy, DNR and USFWS sought a habitat classification model that would use DNR's spatially-explicit forest inventory data to credibly estimate the current and future

[3] Refer to Appendix D, "Occupied Sites Focus Paper," for a description of this survey and modeling work.

location and quality of habitat. To be credible, the model needed to generally identify habitat where it exists, avoid and minimize “false positives” (identifying non-habitat as habitat), avoid and minimize “false negatives” (model not predicting habitat where it actually exists), and distinguish lower-quality habitat in structurally-simple stands from higher-quality habitat in older, complex-structured stands. Additionally, model predictions needed to be reasonably consistent with observed patterns of murrelet habitat use. The model known as “P-stage” was developed by the Science Team to meet these criteria and is modified slightly here to reflect updated information and understanding. Development of the P-stage habitat model was described in detail by Raphael and others (2008, pp. 4.1 – 4.19) and is briefly summarized here, as are the current modifications.

What is P-stage?

P-stage is based on a conceptual model of marbled murrelet nesting habitat (for example, Nelson 1997) as it relates to stand development in natural forests (for example, Franklin and Spies 2002). It attempts to generalize and classify levels of habitat quality as it relates to forest stand characteristics. The model was developed by the Science Team using information from DNR-commissioned murrelet surveys, forest inventory, and forest growth modeling as well as general murrelet and silvicultural science.

> Probability of occupancy increased with stand development from the simple-structured, large-tree exclusion stage through the complex-structured, “fully-functional” stage.

Developing the P-stage Model

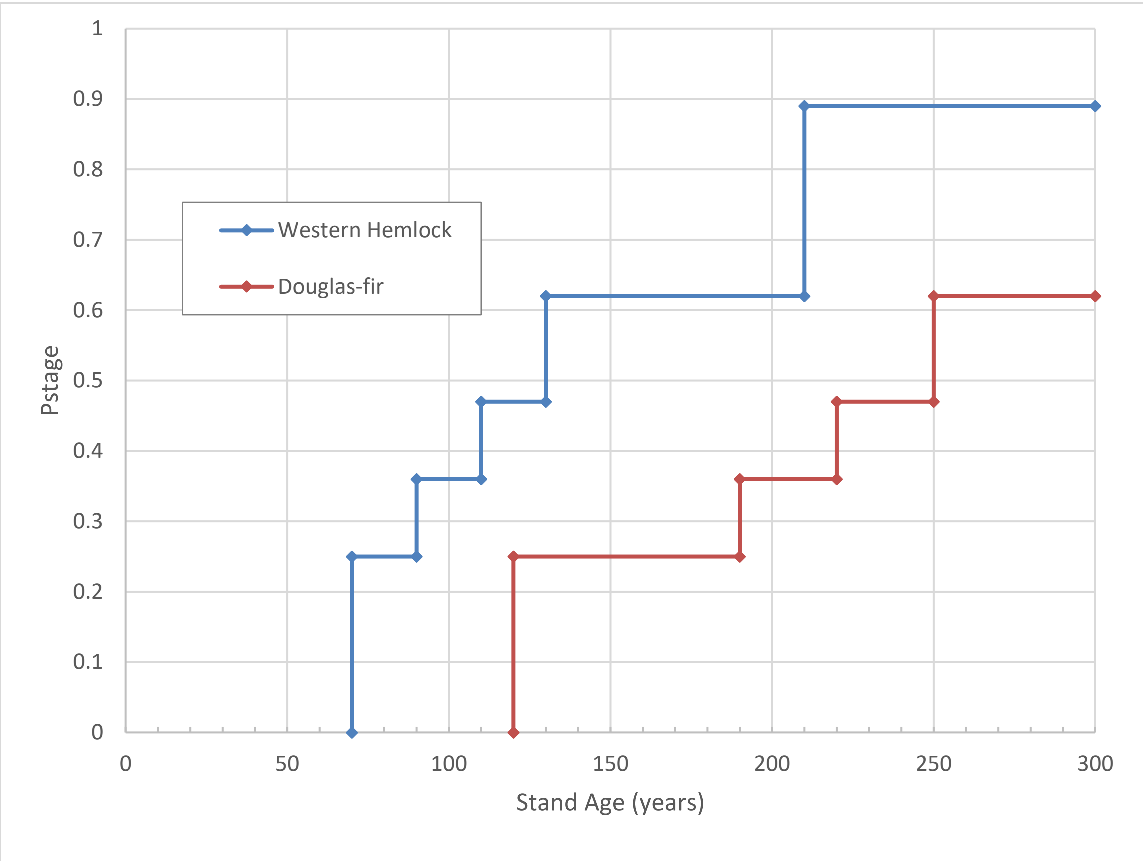
P-stage was developed by the Science Team in order to estimate murrelet habitat quality based on DNR’s forest inventory. DNR commissioned murrelet surveys[4] to screen forest stands for murrelet use, resulting in their binary classification as occupied or not. Forest inventory data from 355 murrelet survey sites in southwest Washington were used in logistic regression analysis to estimate the probability of occupancy based on two forest attributes widely acknowledged to be important components of nesting habitat, platform abundance and canopy complexity. Platform abundance was estimated with the model used by Washington State Forest Practices (Duke 1997), which was developed with data from private forest lands in southwest Washington and is based on the relationships of platform presence and abundance with tree size. An algorithm that estimated canopy layering based on gaps in tree-height distribution (Crookston and Stage, 1999) provided an index to canopy complexity. Platform abundance, canopy layering, and their interaction (platforms * layers) were found to be associated with higher probabilities of occupancy, but were not perfect predictors. However, model predictions clearly supported that probability of occupancy (habitat quality) increased with stand successional development (DNR 2004) from the simple-structured “large-tree exclusion” stage at least through the complex-structured “fully-functional” stage (which provides functions of “old-growth”), as represented in the 355 sites in southwest Washington.

The Science Team examined this relationship of habitat quality increasing with platform abundance and canopy layering, observing that it paralleled patterns of stand successional development. The Team generalized a set of assumptions that quantified habitat quality as a function of stand age and dominant

[4] Refer to Appendix D, “Occupied Sites Focus Paper,” for more details about occupancy surveys.

tree species composition (Raphael and others, 2008). Five stand development stages (DNR 2004) were assumed to have some value as murrelet habitat, and forest growth models were used to generalize the relationship of these five stages with stand age.[5] Stands were classified into stages based on forest inventory estimates of age and species composition, which also predicted the age at which a stand would transition into a higher quality stage (Figure 1).

Figure 1. Ages at Which Naturally-Regenerated Forest Stands Transition among P-stage Categories According to the P-stage Model

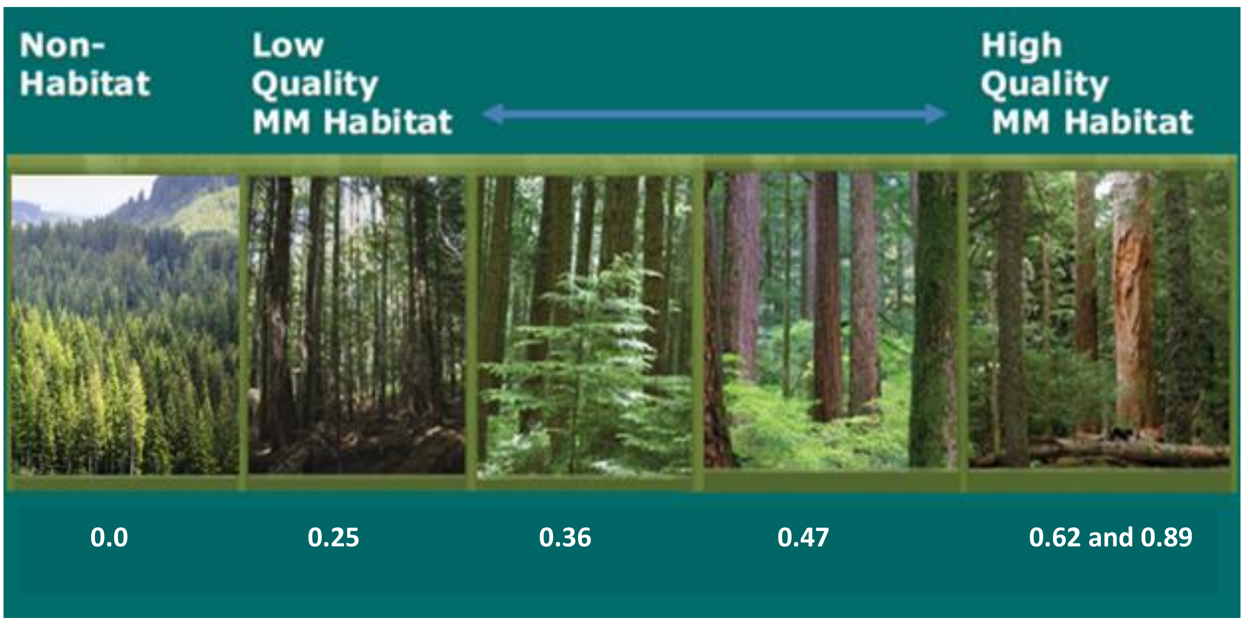


[5] Refer to Figures 4-2 and 4-3 in the Science Team Report (Raphael and others, 2008).

Stands dominated by Douglas-fir rather than western hemlock or other shade-tolerant species were predicted to develop habitat quality more slowly (Raphael and others, 2008). The value that indexed “habitat potential” based on stand development stage was called P-stage to reflect its origins in the logistic regression analysis that predicted “p,” the probability of use. Stands were classified as non-habitat (P-stage 0) or as one of five stages of increasing quality (.25, .36, .47, .62, .89), from the lowest-quality stage that had consistent use (large tree exclusion) to the stage with the highest usage rates (fully-functional) (Figure 2). Those assumptions were used to evaluate conservation opportunities on DNR-managed lands in southwest Washington and the Olympic Peninsula (Raphael and others, 2008).

The value that indexed “habitat potential” based on stand development stage was called “P-stage” to reflect its origins in the logistic regression analysis that predicted “p,” the probability of use.

Figure 2. How the P-stage Model Associates Key Stand Characteristics with Stepwise Development of High Theorized Marbled Murrelet Habitat



Updates to the P-stage Model

The P-stage model of Raphael and others (2008) was modified slightly to apply more broadly across all DNR-managed forests in western Washington and to incorporate updated information and understanding of murrelet habitat and stand development. The most significant update was to the plan area, which was expanded beyond the four coastal HCP planning units analyzed by the Science Team to include the North and South Puget planning units. This approximately doubled the analysis area. Stand origin categories of naturally regenerated versus planted were included to avoid predicting that late 20th century plantations with few or no legacy trees would develop into habitat during the 50-year analysis projections. This would allow model predictions of habitat development in naturally-regenerated stands that often include considerable biological legacies due to historical timber harvest methods. Small adjustments were also made to the predicted rates of transition among P-stage classes (Table 1). The Science Team applied P-stage values to forest habitat within 40 miles of high-use marine habitat (Raphael and others 2008) and discounted those values by 0.25 at greater distances; the current approach applies the values to all habitat within 55 miles of marine water, with discounts applied to some regions with little or no documented murrelet use (refer to Appendix H, "Potential Impacts and Mitigation Focus Paper," for a description of how P-stage values are adjusted for geography and edge effects across the landscape). An additional adjustment acknowledged the demonstrably high value of known *occupied* habitat, which was classified as P-stage 1 (a value not represented in the Science Team report).

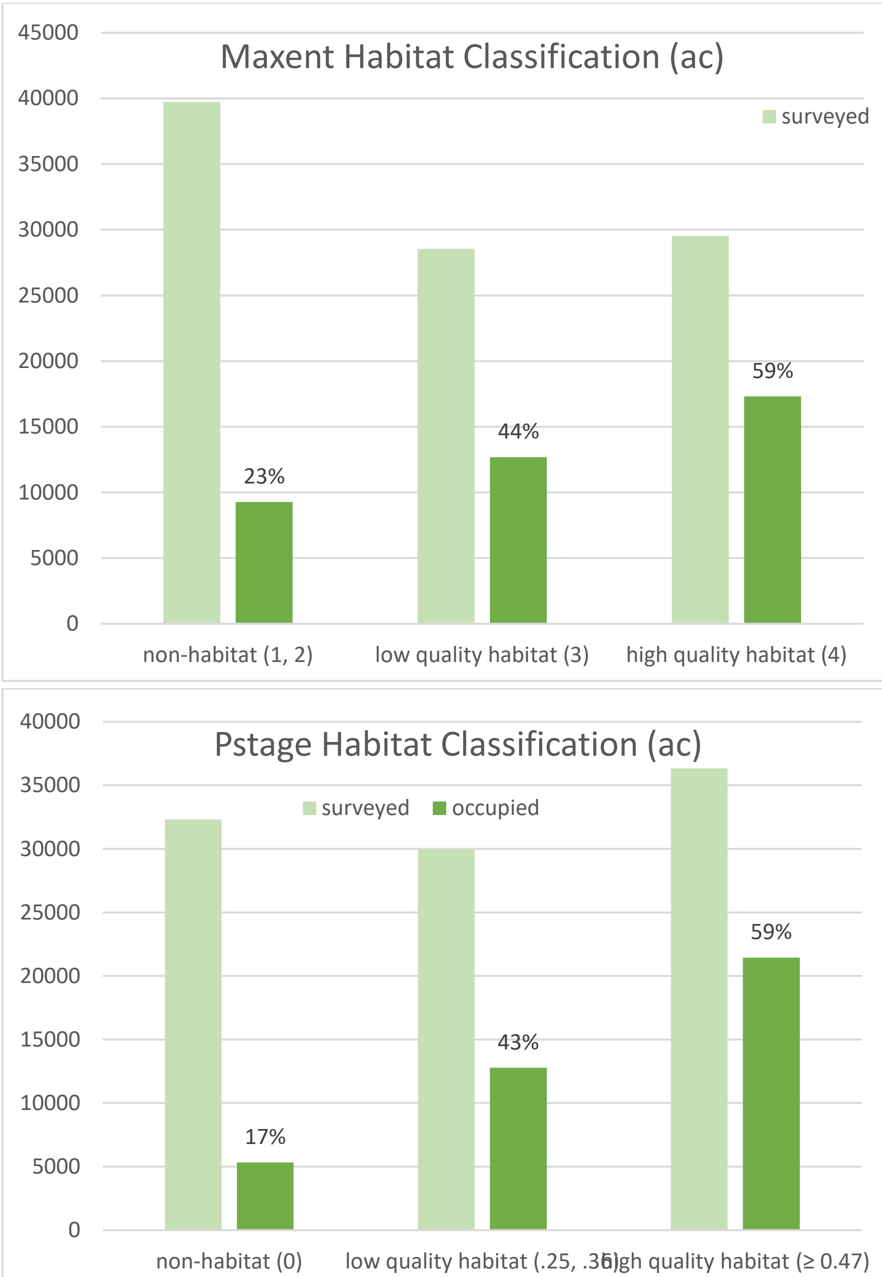
Table 1. Ages at which stands transition among P-stage categories, by dominant tree species, for modelling decisions

	Relative Stand Age (years)	
P-stage (value)	**Western hemlock**	**Douglas-fir**
0.25	70	120
0.36	90	190
0.47	110	220
0.62	130	250
0.89	210	NA

How Does P-stage Compare to Other Models in Estimating Habitat?

To evaluate a model's performance, the normal procedure is to compare predicted results with an observed set. The ratio of observed over predicted results provides a measure of the model's performance. Because there are no agreed upon biological definitions of murrelet habitat or habitat quality, it is not possible to have an observed data set that captures varying habitat quality. Instead, evidence regarding the accuracy of Maxent and P-stage predictions was gathered by examining model predictions at DNR murrelet survey sites comprising nearly 100,000 acres (refer to Appendix D, "Occupied Sites Focus Paper," for a description of these surveys). Given the hypothesis that murrelets avoid non-habitat and preferentially occupy higher-quality habitat, the ratio of occupied to surveyed acreage (occupied ÷ surveyed) should be near zero for non-habitat, and increase as model-predicted habitat quality increases. Falxa and Raphael (2016) summarize Maxent categories 3 and 4 as habitat and categories 1 and 2 as non-habitat. They also consider categories 3 and 4 to represent a gradient in habitat quality. Figure 3 suggests that both P-stage and Maxent predictions are in accord with the murrelet's hypothesized pattern of habitat use, although both models identify significant portions of occupied sites as non-habitat.

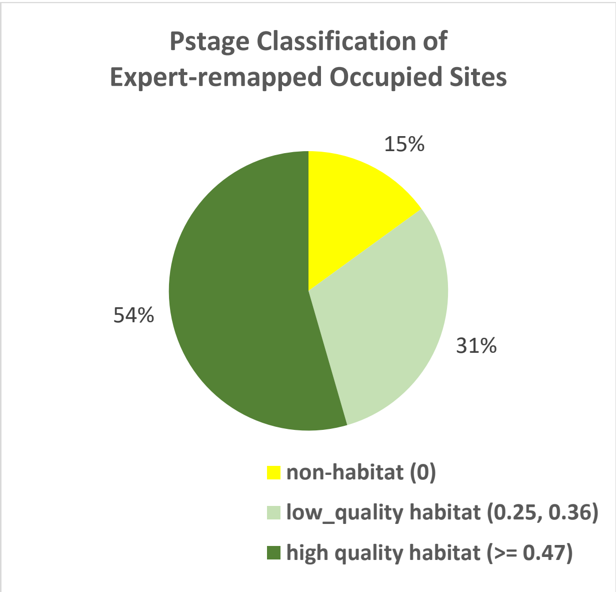
Figure 3. Habitat Classification by the Maxent and P-stage Models for DNR-Managed Land Surveyed for Murrelets and for Occupied Sites Located with those Surveys (percentages reflect occupied/surveyed acres within classes)

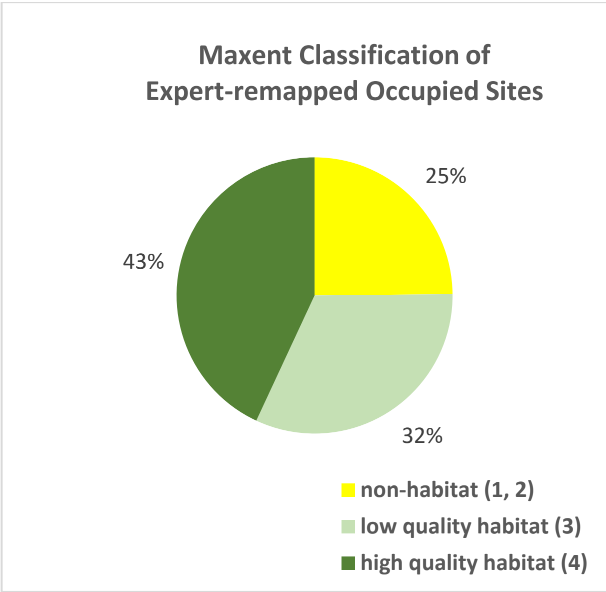


Expert review (Raphael and others 2008) of occupied sites as they were originally mapped under the 1997 HCP resulted in the delineation of approximately 16,300 more acres (including surveyed and unsurveyed areas) asoccupied habitat. Assuming that this expert re-mapping provides a more biologically appropriate delineation of murrelet habitat, Maxent and P-stage habitat classifications of those re-mapped occupied sites can also be evaluated. Model-based estimates of the composition of those areas should conform to the prediction that occupied murrelet sites are predominantly higher quality habitat, with lesser amounts of low quality habitat and little non-habitat.

As illustrated in Figure 4, both models identify that predicted distribution, with higher quality habitat comprising the most abundant group under Maxent (43%) and P-stage (54%) classifications. However, both models identify significant amounts of occupied sites as non-habitat, Maxent 25% and P-stage 15%.

Figure 4. Maxent and P-stage Classifications of 61,000 acres of Expert-mapped Occupied Murrelet Sites on DNR-Managed Land (percentages are class/total area of occupied sites)





It appears that both Maxent and P-stage provide reasonably consistent habitat estimates for areas surveyed for murrelets and for areas found to be occupied. Model predictions of habitat classes at occupied sites provide information on the ability of the respective models to identify habitat where it exists and suggest that while both models perform "reasonably," neither model can identify all habitat. While evidence is less direct, some of the model-predicted habitat by either model that was found unoccupied with surveys may actually be non-habitat. However, the general alignment of both models with predictions based on murrelet biology, the gradient of occupancy rates found with murrelet surveys and the composition of occupied sites, suggests that either model provides appropriate estimates of current location and quality of habitat.

Although no conclusive comparisons of model performance can be made, habitat predictions of the P-stage model align slightly better with hypothesized murrelet habitat relationships, with a lower occupancy rate in non-habitat (Figure 3) and higher proportions of habitat and high-quality habitat composing occupied sites (Figure 4). P-stage appears to be the best available stand-level murrelet habitat model for

DNR-managed land because it is the only model that meets all requirements of USFWS and DNR for development and assessment of the long-term conservation strategy (Table 2).

Table 2. Criteria-based Comparison of Three Habitat Classification Models

Model Criteria	P-stage	Maxent	Interim Strategy (reclassified model)
1.Based on relationship between nesting biology and forest composition	✓	✓	
2. Applicable to all DNR-managed lands in the analysis area	✓	✓	
3. Simple rather than complex	✓		
4. Scale and resolution consistent with DNR forest inventory	✓		
5. Habitat classifications demonstrably consistent with contemporary murrelet science	✓	✓	✓
6. Consistent with DNR forest modeling	✓		

How are Uncertainties in P-stage Model Predictions Addressed?

Hilborn and Mangel (1997) describe two broad types of uncertainty that influence our ability to make inference from ecological models: 1) uncertainty in generalizing and quantifying ecological *processes*, and 2) uncertainty in ecological data gathered from *observations*. Both process and observation uncertainty affect conclusions derived from the P-stage habitat model. Murrelet biological responses (processes like habitat selection, nesting rates, and nest success) are more variable and unpredictable than can be acknowledged within our simplistic model of habitat quality, or in the binary classification of murrelet habitat as “occupied” or not. Likewise, forest structure, composition, and growth are processes that are more complex and subject to many more influences than can be incorporated into the P-stage model. Findings from our sample-based forest inventory and murrelet surveys can be influenced by sampling and measurement error and other forms of observation uncertainty.

Predictions of the P-stage model cannot be perfectly accurate; the model classifies habitat quality by discrete groups, while habitat quality in nature is more likely a continuous gradient. Murrelets likely select habitat based on a more complex suite of environmental cues than platform abundance and canopy layering, and further specificity is lost in the generalization of those elements of stand structure by age-class. Because of these and other uncertainties, some habitat will be overlooked, some non-habitat will be mistakenly identified as habitat. Some habitat will also be mistakenly classified as higher or lower quality than its actual state, and transitions among habitat quality classes will not perfectly follow predictions. Some of these uncertainties and their possible influences on evaluating and selecting a conservation strategy are summarized and discussed below.

If P-stage predictions were consistently biased, there would likely be a directional effect on outcomes of the conservation strategy. For example, if model predictions consistently under-estimated habitat quality, habitat conservation would likely be less effective because some current habitat and forests that would grow into habitat will be overlooked. If habitat quality were consistently over-estimated, habitat conservation would likely be less efficient because some non-habitat would be assigned to conservation pathways but would not serve its intended purpose. Unbiased error can also affect conservation outcomes with effects of under- and over-estimates as noted above, but if those errors were approximately balanced then their effects would be manifest but diluted compared to consistent, directional error. Key components of the P-stage model are examined for theory and/or evidence that could suggest its predictions are biased.

SCALE AND RESOLUTION

The scale at which murrelets select nesting habitat is not known. Clearly, these seabirds need an appropriate nest platform in a context that provides stability and security during the nesting season. Across the nearly 3,000 miles of coast they inhabit in North America, those fine-scale elements of nesting habitat are rather constant but as the view expands beyond the immediate nest site, the environment becomes increasingly indistinguishable from its surroundings (McShane et al. 2004). This uncertainty over the scale at which habitat is distinguished from non-habitat, and how to distinguish among levels of habitat quality is likely responsible for much uncertainty in all habitat modeling and delineation exercises. Raphael et al. (2015) discuss this source of uncertainty in their Maxent model which predicts and maps murrelet habitat across three states at the scale of 30 m square pixels (the resolution of their satellite imagery), generalized from characteristics of the target pixels and its immediate neighbors (9 pixels total, approximately 2 acres) although their multivariate habitat model also incorporates broader-scale influences from the surrounding 50 hectares (147 acres). The P-stage model predicts and maps habitat over DNR-managed land at the scale of forest inventory units (in other words, stands as footnoted above) which average 48.7 acres in western Washington with 82% of nearly 19,000 stands between 5 and 100 acres. Stand-level metrics are developed from on-ground measurements at a network of sample plots located at approximately one plot per five acres. The "suitable habitat block" model, which has been mainly used for project-level planning and implementation, identifies and delineates habitat based on tree-by-tree inspection and arbitrary thresholds for the density of platforms observed (two per acre), the inter-tree distance between platform-bearing trees (300 feet, 92 meters), and minimum patch size (five acres).

Wiens (1976) cautioned researchers to avoid our human preconceptions and focus habitat research at scales important to the organisms of interest. Absent knowledge of the scale, or scales at which murrelets recognize and select nesting habitat, the habitat models noted above mainly focus around human perceptions of forest habitat at scales appropriate to the geographic scope of their unique applications (range-wide, estate-wide, project-level) using the resolution of available data. Thus even if each model classified habitat similarly, their mappings would differ because small habitat areas or inclusions of non-habitat would be variously overlooked depending on resolution. If murrelet habitat consistently occurred in habitat patches too small to be recognized with DNR's forest inventory, P-stage would fail to identify much habitat. However, the consistent broad-scale relationship of murrelet numbers with habitat area as identified with a variety of habitat models (Burger 2002, Raphael and others 2002, Raphael and others 2015) and the consistent patterns of murrelet inland habitat use in identifiable habitat patches (in other words, “stands”) as identified with a variety of methods (for example, McShane and others 2004) suggest that the scale and resolution of P-stage predictions are appropriate to identify most murrelet habitat.

FOREST STANDS

Forest stands, by definition, are a construct of human perception. DNR’s current forest inventory is collected at sample plots, which comprise approximately one percent of stand area for overstory trees (where potential murrelet nest sites occur). Thus, even though stands were delineated from high-resolution aerial photography based on apparent similarity of vegetation and topography, considerable fine-grained heterogeneity within stands is obscured when stand level averages are compiled from plot data. Consequently, discrete areas of habitat could be missed within stands with average characteristics of non-habitat or vice-versa. Some murrelet nests have been located in what appear to be unsuitable forest conditions (Bradley and Cooke 2001, Bloxton and Raphael 2009) although they were generally in landscapes dominated by older forest. These discoveries probably reflect the inability of coarse-grained, stand-level classifications to recognize rare structural elements or small patches of murrelet habitat. However, the great majority of murrelet nests have been located within forests more broadly recognizable as murrelet habitat (for example, McShane and others, 2004), lending confidence that stand-level habitat classification can identify most murrelet habitat.

FOREST GROWTH, STAND CHARACTERISTICS, AND HABITAT DEVELOPMENT

The P-stage model simplifies the relationship of murrelet habitat quality with stand development to three stand characteristics: origin, dominant species, and age. But forest growth and the development of murrelet habitat that accompanies it are much more complex and unpredictable processes than represented by that simple model. Observation uncertainty in the forest inventory-based estimates of stand characteristics adds to the uncertainty that accompanies P-stage predictions of habitat quality. However, comparison of P-stage classifications with murrelet survey findings (Figure 3) and habitat mapping at occupied sites (Figure 4) do not suggest that P-stage provides biased estimates of murrelet habitat quality.

FIELD OBSERVATIONS

Some areas predicted as murrelet habitat by P-stage appear to lack abundant trees with platforms and/or individual trees with abundant platforms. Likewise, some predicted non-habitat contains trees with platforms and some of the area mapped as occupied is classified by P-stage as non-habitat. These observations can be proposed as evidence that P-stage mistakenly classifies some non-habitat as habitat and overlooks other habitat. However some areas mapped as occupied were found to lack platforms as well, lending an additional dimension of uncertainty to comparisons of expert- and model-based habitat predictions. While some habitat is certainly overlooked just because of the scale issues summarized above, it is more difficult to contend that non-habitat is mistakenly classified as habitat because of the probabilistic nature of P-stage predictions. For example, P-stage 0.25 is so classified because stands with that general suite of characteristics are occupied about one-fourth as frequently as the highest quality habitat. The generalized probability of use that P-stage classes represent encompasses within-class, among-stand variability in habitat quality, behavioral variability among murrelets, and other sources of variability. Thus the lack of observable habitat characteristics in some P-stage habitat can be considered to be within the scope of model predictions. The overall patterns of “selection” among P-stage classes found with DNR murrelet surveys (Figure 3) and the classification of habitat identified as belonging to occupied sites (Figure 4) demonstrates the general applicability of the model even though some predictions do not conform to field observations.

Planning with Uncertainty

USFWS and DNR conclude that there is an unknown level of uncertainty in P-stage predictions of current and future habitat. However, the general applicability of the P-stage model predictions outweigh their uncertainty for this conservation planning effort. We can acknowledge this uncertainty and proceed with developing and implementing a conservation strategy using P-stage habitat predictions for three basic reasons: 1) the apparent prevalence of reliable model predictions relative to those clouded by uncertainty, 2) the need to develop and implement a conservation strategy with this uncertainty in mind , and 3) existing policies and management procedures, as well as conservation planning approaches safeguard against high levels of risk associated with this uncertainty. Those additional cautions include:

> USFWS and DNR concluded that there is an unknown level of uncertainty in P-stage predictions of current and future habitat, but also that the general applicability of P-stage model predictions outweigh their uncertainty.

- Habitat conservation is geographically extensive in all alternatives.
- Occupied sites were expanded to include sites where above-canopy circling was observed, and to include expert-identified contiguous habitat regardless of survey findings or previous habitat classification. Protection of expanded occupied sites and buffers are a component of all but one alternative.
- All alternatives propose to retain the majority of identified current and potential future habitat.
- Current and future habitat is abundant in LTFC. It is likely that much of the “overlooked habitat” is prevalent in LTFC and is already in conservation status.
- Some alternatives propose the retention of all “higher quality” habitat.
- Under most alternatives, the majority of habitat conservation and development occurs nearby but outside of occupied sites.
- Estimation of impacts and mitigation are based on the same assumptions so there is an intrinsic balance.

How is P-stage Applied in the Development of the Long-term Strategy?

P-stage is being used for the long-term conservation strategy as a baseline for determining habitat quantity and quality on DNR-managed lands over the life of the 1997 HCP. P-stage values are used to identify key areas to focus conservation, as well as in the calculation of take and mitigation. It is important to recognize that there are other factors that influence the probability of occupancy of a forest stand by murrelets, including proximity to high-quality marine habitat, proximity to other occupied sites, and habitat fragmentation. The P-stage model does not, by itself, account for these factors when evaluating habitat. However, the analytical framework adjusts P-stage values to reflect edge effects, geographic location, and other important factors affecting habitat quality (refer to Appendix H, “Potential Impacts and Mitigation Focus Paper”). In addition, the conservation alternatives being developed account for these factors when designating potential habitat for long-term protection under the 1997 HCP.

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Long-term Forest Cover Focus Paper

Areas of Long-Term Forest Cover

Focus Paper #2

This focus paper was part of a series presented to the Board of Natural Resources in October and November 2015 to inform development of the marbled murrelet long-term conservation strategy alternatives.

■ Introduction

Evidence from most research on marbled murrelet nesting ecology supports the murrelets' requirement for complex-structured forests with large trees. These trees provide large, moss-covered limbs that become nesting platforms. Other research identifies impacts from timber harvest on the availability of nest sites, and on nest success due to increased predation on eggs and nestlings near forest edges. Murrelets therefore rely on conifer-dominated forest stands with large interior areas and high numbers of large, old trees. Forest stands with these characteristics provide nesting opportunities, contain limited amounts of edge, and provide cover from predators and adverse weather (Ralph and others 1995, cited in McShane and others 2004). These types of forest stands can be found on DNR-managed lands within the range of the marbled murrelet. In many cases, these stands are already designated by existing DNR policy to provide conservation benefits. The marbled murrelet long-term conservation strategy identifies forest lands that will be managed as areas of long-term forest cover (LTFC), which may have current habitat or have the capability to develop into the types of structurally complex forests needed for nesting by the murrelet. These areas will be managed to maintain forest cover over the life of the *State Trust Lands Habitat Conservation Plan* (1997 HCP).

■ How do DNR-managed Forest Lands Contribute to Marbled Murrelet Conservation?

DNR-managed forest lands are subject to several laws and department policies guiding their management. The following documents have the most direct impact on how forests are managed for purposes of marbled murrelet conservation:

- The 1997 HCP, a 70-year agreement between the U.S. Fish and Wildlife Service and National Marine Fisheries Services (the Federal Services) and DNR, describes a set of management strategies that DNR employs to offset any incidental take caused to individual listed animals, and promotes conservation of the species as a whole. The1997 HCP was amended in 2004 in the Klickitat Planning Unit to better implement northern spotted owl habitat conservation strategies.[1] The 1997 HCP included an *interim strategy* for marbled murrelet conservation. In addition, concurrence letters between DNR and U.S. Fish and Wildlife Service further specified procedures for identifying and protecting marbled murrelet habitat in the North Puget (2007) and South Puget (2009) HCP planning units.
- The 2006 *Policy for Sustainable Forests* (PSF) contains the vision of the Board of Natural Resources and DNR for the management of current and future forests on state trust lands. PSF policies are specifically designed to achieve DNR's fiduciary responsibilities by generating revenues for trust beneficiaries, while meeting DNR's obligations under the 1997 HCP.

The analysis area for the marbled murrelet long-term conservation strategy includes just over 1.3 million acres of DNR-managed lands.[2] These lands are managed for a multiple set of objectives including timber production, conservation, recreational and resource land uses. With such a large area and variety of land types and land uses, the development of a long-term conservation strategy takes advantage of a landscape planning approach towards conservation.

DNR collects and maintains information on the forest lands it manages. These data are used to determine where, when and how timber harvest is likely to happen, as well as where on the landscape forests are likely to be maintained and/or conserved over time. For example, some forest stands may be deferred from harvest because they are designated as existing old-growth forests, or serve as gene pool reserves for native trees species. Areas may also be deferred from harvest due to slope stability issues or other local knowledge of ecologically, socially, or culturally important areas. Other forest areas may be managed to maintain forest cover or certain forest structural conditions to achieve wildlife habitat objectives for species covered by the 1997 HCP (including the northern spotted owl, salmonids, and other aquatic and riparian obligate species). DNR also manages lands under the state Natural Areas Preserves Act, which dedicates Natural Areas (including Natural Resource Conservation Areas and Natural Area Preserves) in perpetuity for education, scientific research, and conservation of native biological diversity. Together,

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[1] Washington State Department of Natural Resources. 2004. HCP Amendment No. 1, Administrative Amendment to the Northern Spotted Owl Conservation Strategy for the Klickitat HCP Planning Unit, April 2004.

[2] Refer to Appendix B, "Analytical Framework Focus Paper," which describes the analysis area in more detail.

these DNR forest lands are managed to maintain forest cover[3] for conservation; they provide the building blocks for a landscape approach to the long-term conservation strategy for the marbled murrelet.

The conservation strategy defines these areas as LTFC, which may provide potential nesting habitat for marbled murrelet or insulate that habitat from impacts from forest management activities, both now and in the future. This approach implements a key objective of the marbled murrelet conservation strategy.[4]

■ What are Areas of LTFC?

Areas of LTFC can be found throughout DNR's managed forest landscape. These areas are defined and mapped using GIS information from DNR's databases.[5] Areas of LTFC come in various shapes and sizes, and when in a strategic location and suitable habitat condition provide nesting opportunity for the marbled murrelet.[6] LTFC includes the following types of lands:

- Natural area preserves
- Natural resources conservation areas
- Northern spotted owl habitat
- Riparian management zones
- Wetlands
- Areas of slope stability concern
- Gene pool reserves
- Old-growth
- Local knowledge of ecological/social and culturally important areas
- Marbled murrelet occupied sites[7]
- Areas specifically designated for marbled murrelet conservation in strategic locations under each of the alternatives.

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[3] "Forest cover" as used here refers to a relatively closed canopy structure, which may provide cover, security and potential nesting habitat to marbled murrelets.

[4] Refer to Objective #2 of the marbled murrelet conservation strategy: "Provide forest conditions in strategic locations on forested trust lands that minimize and mitigate incidental take of marbled murrelets resulting from DNR's forest management activities. In accomplishing this objective, DNR and USFWS expect to make a significant contribution to maintaining and protecting marbled murrelet populations."

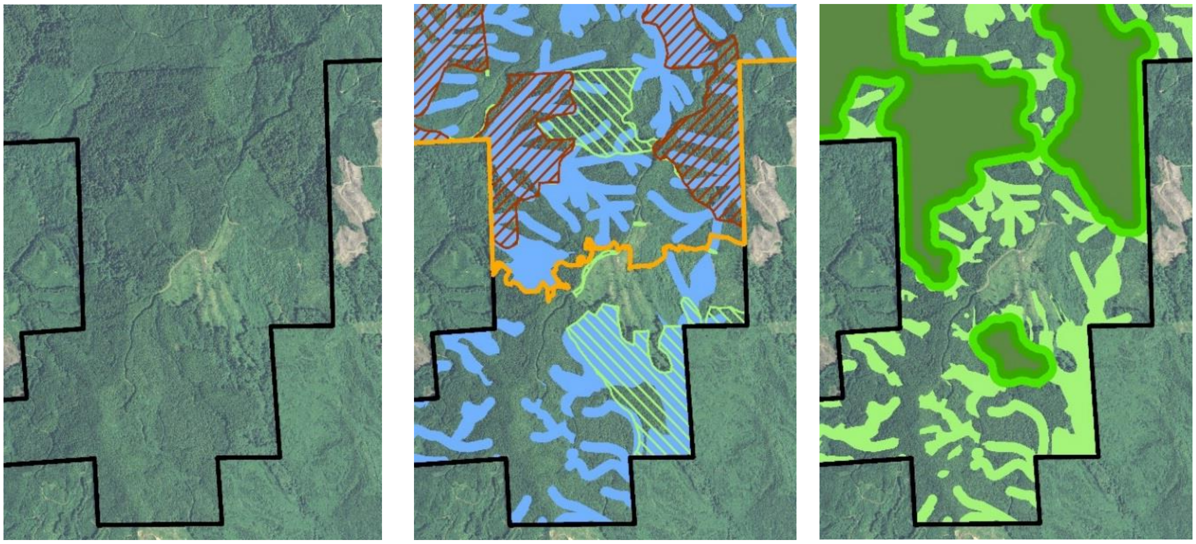
[5] DNR Large Data Overlay, 2015.

[6] Refer to Objective #2 of the long-term conservation strategy: "Provide forest conditions in strategic locations on forested trust lands that minimize and mitigate incidential take of marbled murrelets resulting from DNR's forest management activities. In accomplishing this objective, we expect to make a significant contribution to maintaining and protecting marbled murrelet populations."

[7] Refer to Appendix D, "Occupied Sites Focus Paper."

These areas, layered together (as illustrated in Figure 1), create blocks of land that contribute to marbled murrelet conservation, if the structure and complexity of the forest within provides nesting habitat and security from predation.[8]

Figure 1. Layering Data to Map Areas of LTFC



Block of DNR-Managed Land

Occupied sites, riparian zones, other protected areas

Areas layered together to form LTFC (interior forest in darkest green, edges in lighter greens)

The precise boundaries of some categories of LTFC are accurately mapped in the DNR databases. Examples include gene pool reserves and natural areas. These boundaries are not expected to change throughout the life of the HCP. Other categories of LTFC are not precisely mapped but are approximated until field inspections can more accurately define correct boundaries. LTFC associated with riparian areas, wetlands, and unstable slopes are examples where the boundaries may be adjusted when site-specific information becomes available. Although the exact location of LTFC associated with riparian areas can change with field verification, the total acres of LTFC associated with these deferrals is a reasonably accurate estimate of the total LTFC expected to be retained on the landscape.

[8] The varying quality of the habitat found within LTFC is analyzed using a mathematical model, described in Focus Paper #3, "Estimating the Location and Quality of Stands of Marbled Murrelet Habitat." *Note: This paper will be available in late November 2015.*

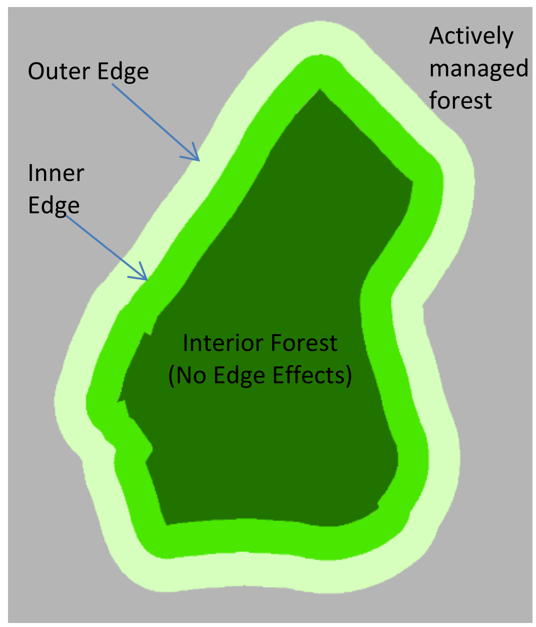
■ How Does LTFC Provide Nesting Security to Murrelets?

LTFC is assumed to conserve habitat by protecting current and potential nest sites from harvest and other land uses in the managed forest. The shape and amount of interior forest patches within LTFC is a critical factor in nesting success and security. Forest edges created from harvest or other types of openings (e.g., roads) impact this security. LTFC can be classified into one of three forest zones that support varying levels of marbled murrelet conservation. These zones are influenced by the condition of the adjacent managed forest, which is characterized as "hard-edged," "soft-edged," or in a "no-edge" state. In addition, some areas, referred to as riparian "stringers" (described later in this section), are linear in nature and do not include any interior forest. Beyond these areas is the actively managed forest, where most of the harvest and related activities occur.

Interior Forest

The interior forest (Figure 2) is comprised of forested area (patch) that is at least 100 meters from any type of edge. These interior areas are protected from effects associated with harvest edges. Edge effects include changes in microclimate (such as decreasing humidity), windthrow, changes in vegetative species such as reduction in epiphyte presence, and increased risk of predation (Nelson and Hamer 1995; McShane and others 2004; Van Rooyen and others 2011). Further, impacts to murrelets from disturbance (loud noise and activity that can interrupt breeding and nesting behaviors) is reduced in the interior forest portions of LTFC. (Refer to Appendix H, "Potential Impacts and Mitigation Focus Paper," for a detailed description of edge effects.)

Figure 2. Conceptual Illustration of an Area of LTFC and Edges



Outer Edge

The outer edge of the interior forest patch is located between 0 to 50 meters from the edge of managed forest (Figure 2). Because this area is adjacent to the actively managed forest, edge effects are more pronounced in the outer edge.

Inner Edge

The inner edge (Figure 2) is a forested area located 51 to 100 meters from the edge of the actively-managed forest, and is adjacent to the interior forest patch. The literature indicates that the edge effects from the actively managed forest extend further than 50 meters into the stand, but diminish until there is minimal effect after 100 meters from the managed area (Burger and others 2004).

Hard, Soft, and no Edges

Depending on the age and height of the trees in the actively managed forest, edges can be characterized as either "hard" or "soft." Hard edge effects extend through the outer and inner edges, and occur when the actively managed forest is comprised of young stands (0-20 years old) that are expected to be generally less than 40 feet high. Higher risk of nest predation, and increased microclimate and windthrow effects are all associated with hard edges.

Soft edges are characterized by managed forest stands that are expected to be generally 20-40 years old and 40-80 feet high adjacent to the long-term forest cover.[9] At this stage, interior forest and the outer and inner edges are less affected by predation risk and microclimate and windthrow effects still factor into edge impacts, but to a lesser degree. Trees in the managed forest that are beyond 40 years of age and 80 feet in height are assumed to have minimal edge effects to the interior, and therefore are not counted as edge under the analytical framework.

DNR can assess the edge conditions of managed forest lands in the analysis area using forest inventory and GIS data. This information is used to determine potential impacts to murrelet habitat from forest edges, and to calculate necessary mitigation (refer to Appendix H, "Potential Impacts and Mitigation Focus Paper").

Roads as edges

New and existing forest roads (logging roads) also create edges. Depending on their location relative to murrelet habitat, and whether they are actively used or are undergoing transition back to forest, roads have effects similar to other hard or soft edges. Roads can attract corvids and affect microclimate. (Refer to Appendix H, "Potential Impacts and Mitigation Focus Paper" for a discussion on how roads and other edges impact habitat and mitigation values.)

"Stringers"

Areas mapped as long-term forest cover using GIS will show large and small blocks of LTFC, as well as some narrow strips of land. These narrow strips are termed "stringers," and are predominantly riparian management zones. Stringers are areas less than 200 meters wide and therefore do not have interior forest. Stringers are considered part of LTFC; however, they may not be assigned credit for mitigation under the conservation alternatives.

[9] The tree height and age associations described here are generalized, and may vary somewhat across the landscape depending on site conditions.

Areas Outside LTFC

Forest land outside of LTFC is managed for harvest to meet fiduciary responsibilities to DNR's trust beneficiaries. These are part of the actively managed forest.

■ How does LTFC Differ Across the Conservation Alternatives?

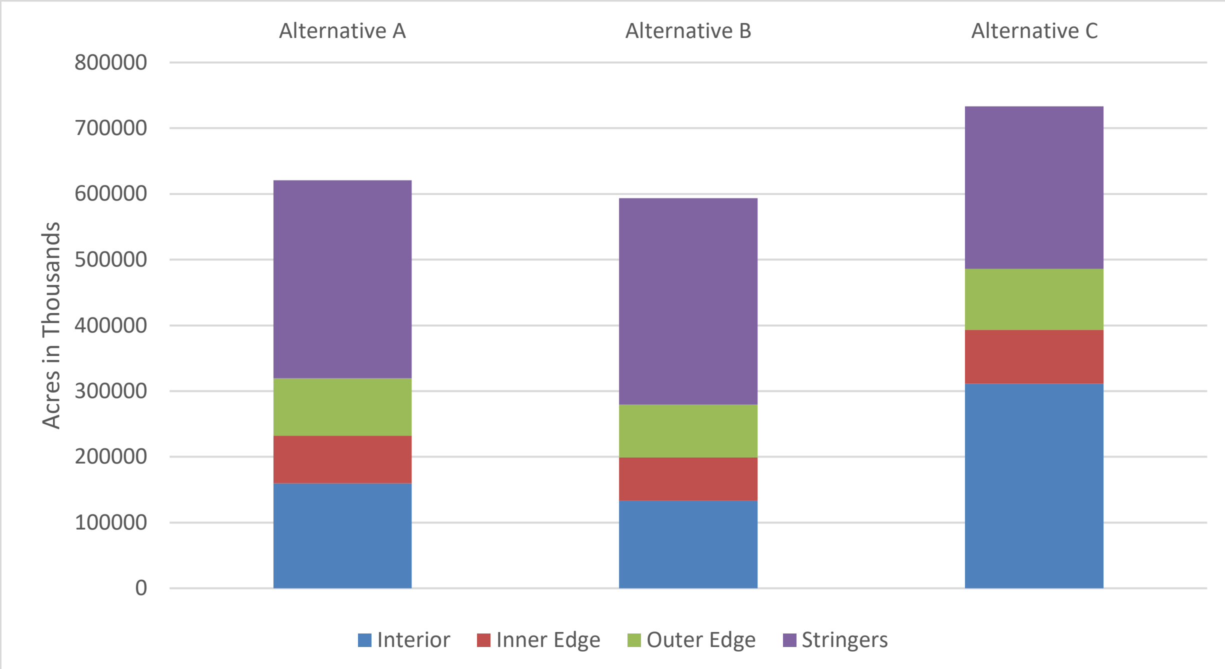
DNR and the U.S. Fish and Wildlife Service are developing alternative approaches to long-term marbled murrelet conservation. These alternatives will be evaluated using a common analytical framework.[10]

Designating areas of LTFC under each alternative allows potential impacts to be quantified, mitigation to be calculated,[11] and conservation benefits to be evaluated. The amount and composition of LTFC varies among alternatives (refer to Figure 3 for an example). The proportion of interior forest to outer and inner edges may vary, or the occupied sites or conservation areas that are included may be different.

These differences in composition mean that the geographic extent of LTFC (how much of and where on the landscape it is located) will differ among alternatives. All LTFC is intended to provide conservation benefit to the murrelet. However, the conservation value of one area of LTFC may be higher or lower than another, depending on its relative habitat quality, its location relative to occupied sites or marine populations, and other factors. The analytical framework takes these factors into account when calculating potential impacts and mitigation through the life of the HCP.

[10] Refer to Appendix B, "Analytical Framework Focus Paper."
[11] Refer to Appendix H, "Potential Impacts and Mitigation Focus Paper."

Figure 3. How the Amount and Composition of LTFC May Differ Across Conservation Alternatives; Data for Illustration Purposes Only (<u>does not reflect the actual alternatives</u>)



■ How Will Areas of LTFC be Managed for Purposes of Marbled Murrelet Conservation?

> Stands within interior areas of LTFC that have marbled murrelet habitat characteristics, or that have the potential to develop those characteristics, will be protected from potential impacts from harvest, edge effects, and other types of disturbance.

Although the exact make-up of LTFC may differ among conservation alternatives, the management objective of LTFC is the same under every alternative: to provide long-term forest cover. Forest stands within areas of LTFC that have murrelet habitat characteristics, or that have the potential to develop murrelet habitat characteristics, will be conserved over the life of the 1997 HCP. No major harvest activities will be allowed within LTFC. The conservation alternatives being developed may allow some thinning or habitat enhancement within areas of LTFC, consistent with the underlying conservation objectives. For example, riparian areas within LTFC may be thinned consistent with DNR's Riparian Forest Restoration Strategy. Management of non-timber harvest land uses will also be addressed under the alternatives.

Management will be consistent with the conservation objective that the quality and quantity of habitat within areas of LTFC is expected to improve as forest stands mature. Mature stands that do not currently have murrelet habitat characteristics will also have the potential to develop into habitat over the life of the HCP.

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