Chapter 5: Marbled Murrelet

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Introduction

In this chapter, we describe expectations of the Northwest Forest Plan (NWFP, or Plan) and review recent science on the ecology and status of the marbled murrelet (*Brachyramphus marmoratus*), with an emphasis on the portion of the species' range that falls within the Plan area. The conservation strategy embodied in the NWFP evolved from designation and protection of a large number of relatively small management areas to an approach based primarily on the designation of fewer large areas, each designed to conserve functioning late-successional and old-growth ecosystems. These were intended to support multiple pairs of northern spotted owls (*Strix occidentalis caurina*) and murrelets, and to conserve habitat for other species associated with older forests.

The marbled murrelet is a small seabird of the family Alcidae (fig. 5-1) whose summer distribution along the Pacific Coast of North America extends from the Aleutian Islands of Alaska to Santa Cruz, California (fig. 5-2). It forages primarily on small fish and krill in the nearshore (0 to 2 mi [0 to 3 km]) marine environment. Unlike other alcids, which nest in dense colonies on the ground or in burrows at the marine-terrestrial interface, murrelets nest in more dispersed locations up to 55 mi (89 km) inland. In the southern portion of the range, including the Plan area

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Figure 5-1—The marbled murrelet is a small seabird of the family Alcidae.

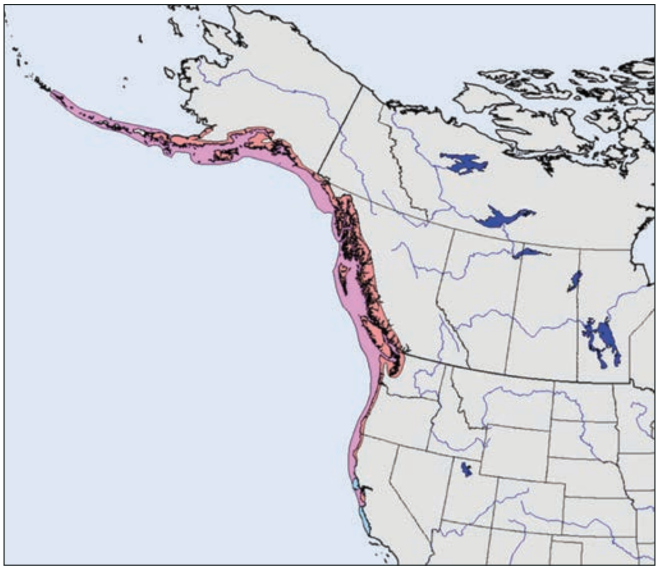

Figure 5-2—Range of the marbled murrelet in North America. Map by Terry Sohl from NatureServe data.

and the area emphasized in this chapter, murrelets typically nest in large coniferous trees in forested areas containing characteristics of older forests. Throughout the forested portion of the species' range, murrelets typically nest in areas containing characteristics of older forests (Baker et al. 2006; Binford et al. 1975; Hamer and Cummins 1991; Hamer and Nelson 1995; Hamer et al. 1994; Hébert and Golightly 2006; Quinlan and Hughes 1990; Ralph et al. 1995a; Singer et al. 1991, 1992; Wilk et al. 2016). The marbled murrelet population in Washington, Oregon, and California nests in most of the major types of coniferous forests (Hamer and Nelson 1995) in the western portions of these states, wherever older forests remain inland of the coast at elevations primarily below the extent of the true fir zone, generally <4,000 ft (1220 m) (table 5-1). Although murrelet nesting habitat characteristics may differ throughout the range of the species, some general habitat attributes are characteristic throughout its listed range, including the presence of nesting platforms, adequate canopy cover over the nest, larger patch size of mature forest, and being within commuting distance to the marine environment (Binford et al. 1975, Hamer and Nelson 1995, Nelson 1997, McShane et al. 2004, Ralph et al. 1995b). Because murrelets do not construct nests, they depend on the availability of platforms, typically tree limbs with a moss or other thick substrate, such as piles of needles collected on limbs near a tree bole, sufficiently large for laying their single egg and raising a nestling (Nelson 1997, Ralph et al. 1995).

Table 5-1—Known inland limits of marbled murrelet nests and detections

	Inland distance		
State/province	Nest[a]	Occupied site	Sources
	- - - *Miles* - - -		
Alaska	33		Nelson et al. 2010, Whitworth et al. 2000
British Columbia	39	41	Jones et al. 2006, Lougheed 1999, Nelson et al. 2010, Ryder et al. 2012
Washington	55	55	D. Lynch, personal communication[b]; Ritchie and Rodrick 2002
Oregon	32	47	Alegria et al. 2002; Dillingham et al. 1995; E. Gaynor, personal communication[c]; Witt 1998a, 1998b
California	24	24	S. Chinnici, personal communication[d]; A. Transou, personal communication[e]

Note: see table on page 338 for metric equivalents.
[a] Includes grounded fledglings and eggshell fragments.
[b] D. Lynch. Personal communication. Fish and wildlife biologist, U.S. Department of the Interior, Fish and Wildlife Service, 510 Desmond Dr., Suite 102, Lacey, WA 98503.
[c] E. Gainer. Personal communication. Wildlife biologist, U.S. Department of the Interior, Bureau of Land Management, 777 NW Garden Valley Blvd., Roseburg, OR 97471.
[d] S. Chinnici. Personal communication. Forest science manager, P.O. Box 712, Humboldt Redwood Company, Scotia, CA 95565.
[e] A. Transou. Personal communication. Environmental scientist, California Department of Parks and Recreation, North Coast Redwoods District, P.O. Box 2006, Eureka, CA 95502; 707-445-6547; atransou@parks.ca.gov.

Individual tree attributes that provide conditions suitable for nesting (i.e., provide a nesting platform) include large branches (ranging from 4 to 32 inches (10 to 81 cm) diameter, with an average of 13 inches (33 cm) in Washington, Oregon, and California) or forked branches; deformities (e.g., broken tops); dwarf mistletoe infections; witches' brooms; and growth of moss or other structures large enough to provide a platform for a nesting adult murrelet (Hamer and Cummins 1991; Hamer and Nelson 1995; Singer et al. 1991, 1992).

These nesting platforms (fig. 5-3) are generally located ≥33 ft (10 m) above ground (reviewed in Burger 2002 and McShane et al. 2004). These structures are typically found in old-growth and mature forests, but may be found in a variety of forest types, including younger forests containing remnant large trees. Since 1996, research has confirmed that the presence of platforms is considered the most important characteristic of murrelet nesting habitat (Burger 2002, Huff et al. 2006, McShane et al. 2004). Platform presence is more important than the size of the nest tree because tree size alone may not be a good indicator of the presence and abundance of platforms (Evans Mack et al. 2003). Tree diameter and height can be positively correlated with the size and abundance of platforms, but the relationship may change depending on the variety of tree species and forest types that murrelets use for nesting (Burger et al. 2010, Huff et al. 2006, Raphael et al. 2011). Overall, nest trees in Washington, Oregon, and northern California have been greater than 19 inches (48 cm) diameter at breast height (d.b.h.) and greater than 98 ft (30 m) tall (Hamer and Meekins 1999, Hamer and Nelson 1995, Nelson and Wilson 2002). Northwestern forests and trees typically require 200 to 250 years to attain the attributes necessary to support murrelet nesting, although characteristics of nesting habitat sometimes develop in younger western hemlock (*Tsuga heterophylla*) forests with dwarf mistletoe.

Marbled murrelets are reported to nest disproportionately on lower slopes and near streams. The recovery plan for the murrelet (USFWS 1997) states, "With respect to slope, eighty percent of nests in the Pacific Northwest were located on the lower one-third or middle one-third of the slope." Hamer and Nelson (1995) showed the mean distance to streams from murrelet nests in the Pacific Northwest to be 159 m (509 ft). In southern California, Baker et al. (2006) found that murrelet nest sites were located closer to streams, and were located lower on slopes than random sites, based on analysis of variance models. Baker et al. (2006) found that nest sites were much closer to streams than would be expected based on randomly available sites within old-growth forests. Nest sites may have been located near streams because these sites afforded murrelets better access from at-sea flyways.

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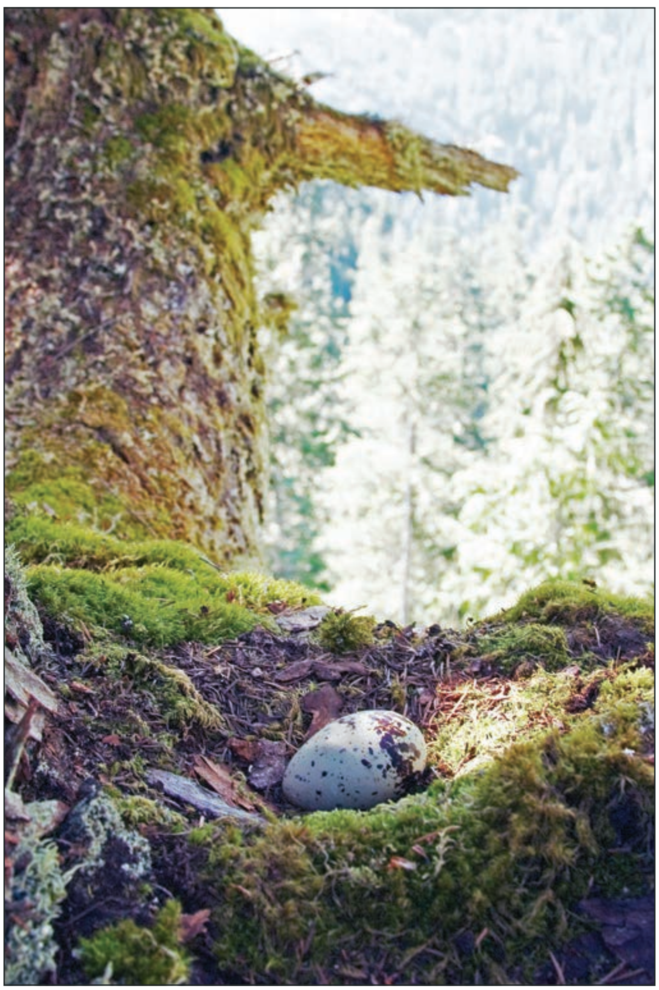

Figure 5-3—Nesting platforms usually include large branches and other structures large enough to provide a platform for a nesting adult murrelet.

Other studies have also found proximity to streams or other openings to be important for murrelet nesting in other regions as well (Hamer and Nelson 1995, Meyer et al. 2004, Zharikov et al. 2006). In British Columbia, Rodway and Regehr (2002) found that forests bordering major stream channels provided high-quality nest habitat for murrelets, with large trees, high epiphyte cover, and many potential nest platforms.

Murrelets travel up to 55 mi (89 km) inland to reach suitable habitat in the northern part of their range in the Pacific Northwest; inland distances narrow in the southern portions of the range (table 5-1). Because murrelets depend on marine conditions for foraging and resting, and on forests for nesting, both marine and forest conditions could limit murrelet numbers. Population declines attributed to loss of mature and old-growth forest from harvesting, low recruitment of young, and mortality at sea, led this species to be federally listed as threatened in Washington, Oregon, and California in 1992 (USFWS 1997), and listed as threatened in British Columbia (Rodway 1990). The murrelet's association with late-successional and old-growth forests and its listed status made conservation of the murrelet an explicit goal in the design of the NWFP.

The NWFP included several elements of protection for murrelet nesting habitat. The Plan's system of reserves was not designed, as it was for the northern spotted owl, with specific goals for the number and spacing of clusters of murrelets. Rather, the system of congressionally reserved lands and late-successional reserves was designed to encompass a high proportion of murrelet nesting habitat thought to exist on federal lands. In addition to the reserve system, the NWFP requires murrelet surveys to be conducted before harvest on any other federal lands in the murrelet's range. If a survey shows likely nesting, then all contiguous existing and recruitment habitat (defined as stands that could become nesting habitat within 25 years) within a 0.5-mi (0.8 km) radius is protected. These occupied sites become small reserves, denoted as LSR3, and are managed to retain and restore nesting habitat.

Guiding Questions

The mission statement for the Forest Ecosystem Management Assessment Team (FEMAT) directed the team to take an ecosystem approach to forest management and particularly to address maintaining and restoring biodiversity on federal forests within the range of the northern spotted owl. In addressing biological diversity, the team was directed to develop alternatives that met, among other things, the objective of maintaining or restoring habitat conditions for the murrelet that would provide for viability of the species (FEMAT 1993: iv). Now, 22 years after the NWFP was initiated, national forests in the Plan area are preparing to revise their forest plans. Accordingly, U.S. Forest Service managers have asked how the NWFP has been functioning to support the murrelet and what new science is relevant to murrelet conservation and management. Managers were polled to develop questions relating to the murrelet (as well as other NWFP issues), and this chapter aims to synthesize relevant science related to these questions:

- Are murrelets maintaining viable populations under current NWFP management?
- Is forest management under the NWFP providing nesting habitat for murrelets as planned?
- What is the latest science surrounding the effects of various treatments (silvicultural and fuels) and wildfire on late-successional, old-growth forests and plantations, and what are the effects on murrelets?
- Does the murrelet use these treated forests after harvest? If so, how? Are there ways to modify harvest to benefit murrelets?
- How do these treated habitats compare to untreated habitat in terms of habitat use and reproductive success?
- How have at-sea conditions affected nearby forest use by the murrelet?

To address these questions, we conducted a thorough literature review, guided by keywords included in the questions, and we emphasized references pertaining to murrelets in the Plan area. We excluded gray literature and other unpublished work. We considered additional literature suggested by public comments. As will be apparent in the text, we found little literature bearing on questions 3, 4, and 5, as they pertain to responses of murrelets to silviculture. We direct readers to Spies et al. (this volume) for a summary of how younger forests respond to silvicultural treatments that might influence murrelet nesting habitat.

Key Findings

NWFP Expectations

The stated objective of the NWFP is to maintain and restore nesting habitat conditions that would provide for viability of murrelet populations, well-distributed along their current range on federal lands (FEMAT 1993: iv). The expectation was that the Plan "…would eventually provide substantially more suitable nesting habitat for murrelets than currently (in 1994) exists on federal lands" (USDA and USDI 1994a). FEMAT used an expert panel to assess the likelihood that nesting habitat on federal lands would support stationary and well-distributed populations of the murrelets. Following the methods described in FEMAT (1993), the murrelet expert panel assigned an 80 percent likelihood that nesting habitat would be of sufficient quality, distribution, and abundance to allow the murrelet population to stabilize, well distributed across federal lands over the next 100 years (Outcome A) under Option 9, the preferred alternative that was eventually adopted (with modifications) as the NWFP. The panel assigned a 20 percent likelihood for Outcome B, under which nesting habitat would be sufficient to allow the murrelet population to stabilize but with significant gaps in the historical distribution that could cause some limitation in interactions among local populations. The panel assigned no likelihood of Outcomes C or D. Thus, the panel's assessment was that the likelihood was high that nesting habitat conditions on federal lands would allow the murrelet population to stabilize and be well distributed throughout its range (FEMAT 1993). In recognition of the major influence of marine conditions on population viability, however, including mortality from oil spills and gill netting, and considering the potentially important role of nonfederal lands, the murrelet panel assigned a second set of ratings that considered the cumulative effects of all major factors. The murrelet panel concluded that the likelihood that the murrelet population on federal lands would be stationary and well-distributed was between 50 and 75 percent. The higher rating was meant to indicate the degree of protection conferred by nesting habitat conditions on federal lands, assuming that all other factors were not limiting; the lower rating from the cumulative effects analysis was an attempt to indicate the greater uncertainty in murrelet persistence, given the importance of other factors beyond federal nesting habitat.

Neither the assessment team nor final supplemental environmental impact statement nor subsequent monitoring plan for the murrelet (Madsen et al. 1999) provided quantitative descriptions of expected murrelet population trends or nesting habitat trends over time that now could be used to assess NWFP performance since its implementation. There are, however, some more qualitative descriptions or assumptions from the period around the start of the assessment team and the record of decision:

- The amount of murrelet nesting habitat had declined over the previous 50 years, primarily because of timber harvesting (Perry 1995, USFWS 1997).
- Murrelet populations are likely to have declined as well, largely in response to loss of nesting habitat (Ralph et al. 1995a).
- Demographic projection models estimated at the time the NWFP was initiated suggested a population decline of 4 to 7 percent per year from 1990 to 1995 (Beissinger 1995).
- Because murrelets have naturally low reproductive rates, population recovery will be slow, on the order of a maximum of 3 percent per year (USFWS 1997).
- No destruction of nesting habitat surrounding active murrelet nesting sites will be knowingly done on federal lands.
- Catastrophic and stochastic events that decrease the quality or quantity of nesting habitat would affect nesting habitat at unknown rates.
- Over the long term, the amount of nesting habitat will increase in reserves as unsuitable forest matures.
- Late-successional reserves will provide large contiguous blocks of nesting habitat with increased interior (180 ft [55 m] or more from edge) nesting habitat.

- Rates of nest depredation would decrease as the amount of interior nesting habitat increases in reserves.
- In the short term (less than 50 years), the availability of nesting habitat may remain stable or decline from losses from fire and other natural disturbances.
- The rate of increase in the amount of nesting habitat will be slow because trees do not develop structures suitable to support nests until they are large and old, often 150 or more years (USDA and USDI 1994a; USFWS 1997).
- Nesting habitat management on nonfederal lands will affect viability of murrelets on federal lands.
- Physical and biological processes in the marine environment, which operate at multiple temporal and spatial scales, also affect short- and long-term population trends of murrelets, independent of nesting habitat quantity or quality.

McShane et al. (2004) developed a population model to predict population change in each of five conservation zones comprising the Plan area (fig. 5-4). Their model, which used annual adult survival estimates obtained from detailed mark-recapture studies in British Columbia (the only such data then available) and fecundity estimates from ratios of juveniles to adults at sea or from mark-recapture studies, predicted annual rates of decline varying from 3 to 5 percent per year over the first 20 years of their simulations in murrelet conservation zones 1 through 5.[2] Rates of decline were generally greater going from north (zones 1 and 2) to south (zone 5). These predictions are in line with those of Beissinger (1995), using models based mostly on comparative demographic data from other alcid species. These models do not directly account for the amount of nesting habitat, thus model projections do not respond to expected habitat trends.

NWFP Monitoring Results for Marbled Murrelets

Population size and trends—
A specific conservation goal of the plan is to stabilize and increase murrelet populations by maintaining and increasing nesting habitat. As described below, population monitoring results to date indicate that the plan goal of stabilizing and increasing murrelet populations has not yet been achieved throughout the Plan area, because while in some areas the population may have stabilized, they have not increased substantially. Murrelet populations were thought to be declining at the start of the Plan, with loss of more than 80 percent of nesting habitat being the central cause for declines and for murrelets being listed as federally threatened (USFWS 1997). Declines were expected to continue for a period (e.g., Raphael 2006), until nesting habitat sufficiently recovers from previous losses to lead to increased fecundity, and populations stabilize and increase (USFWS 1997). The Plan goal of increasing populations recognizes the large historical population declines (Peery et al. 2010, USFWS 1997), and the conservation value of larger populations than were present in 1994.

To evaluate murrelet population status and trends under the Plan, the murrelet effectiveness monitoring program designed a coordinated sampling protocol (Madsen et al. 1999, Raphael et al. 2007) and obtained annual population estimates starting in 2000 by monitoring murrelet populations in nearshore marine waters associated with the Plan area, in Washington, Oregon, and northern California (fig. 5-4). The population monitoring uses boat-based transects and distance estimation methods in those coastal waters, which are divided into five geographic subareas corresponding to conservation zones established in the U.S. Fish and Wildlife Service's recovery plan for the murrelet (fig. 5-4). The monitoring program estimated population size and trend for each conservation zone, for each state, and for all zones combined. Through 2013, the entire Plan area was surveyed annually; starting in 2014 a reduced-sampling design was instituted because of funding constraints, in which conservation zones 1 through 4 are sampled every other year, and zone 5 every fourth year. Details about the sampling and data analysis methods used by the population monitoring program are described elsewhere (Falxa et al. 2016, Raphael et al. 2007).

[2] These zones are defined in the marbled murrelet recovery plan (USFWS 1997): Conservation zone 1 is Puget Sound and the Strait of Juan de Fuca in Washington; zone 2 is the outer coast of Washington to the Columbia River; zone 3 is Oregon from the Columbia south to North Bend (Coos Bay); zone 4 is North Bend south to Shelter Cove, California; zone 5 is Shelter Cove south to the mouth of San Francisco Bay (see fig. 5-2). Zone 6, from the mouth of San Francisco Bay south to Point Sur, California, is outside of the Northwest Forest Plan area.

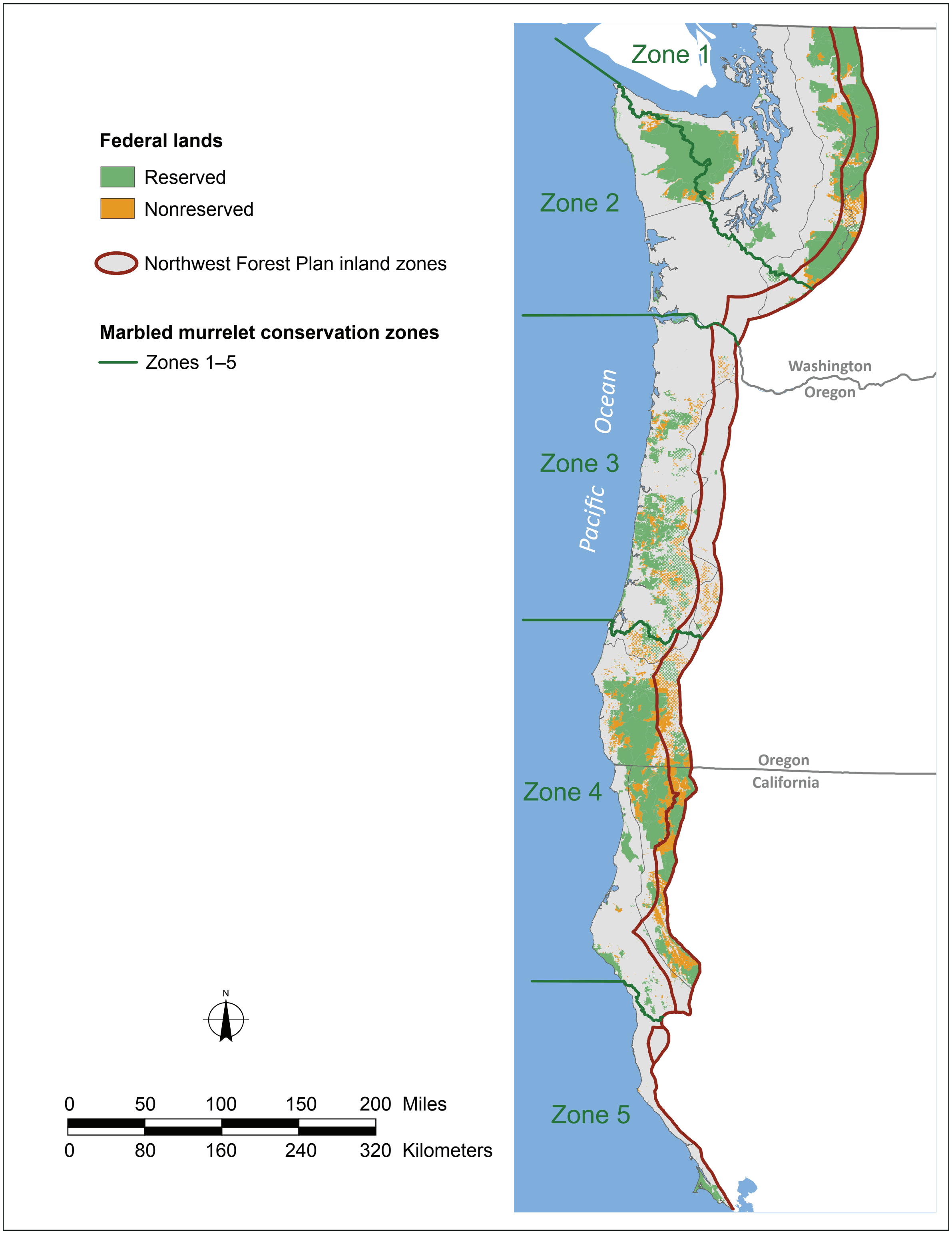

Figure 5-4—Range of the marbled murrelet with boundaries of conservation zones and locations of federal reserves, other federal lands, and nonfederal lands. Also shown are boundaries of the "inland zones" designated by the Northwest Forest Plan; see "Research Needs, Uncertainties, Information Gaps, and Limitations" for a description of these zones.

The 20-year murrelet status and trends report provided estimates through 2013 (Falxa et al. 2016); population monitoring results from 2014 and 2015 have since become available in annual reports (Falxa et al. 2015, Lynch et al. 2016). At the conservation-zone scale, the most recent population estimate shows few murrelets remaining in conservation zone 5 (San Francisco Bay north to Shelter Cove, California; estimate: 71 murrelets, 95 percent confidence interval: 5 to 118) (Lynch et al. 2016); this is consistent with estimates since 2000. Considerably more murrelets remain in the other four conservation zones within the NWFP area, with murrelet numbers, expressed as an average of annual estimates over the the past 4 years with sampling (Lynch et al. 2016) as follows: about 7,600 murrelets in conservation zone 1 (the Strait of Juan de Fuca, San Juan Islands, and Puget Sound in Washington; for 2012–2015); about 2,000 birds in conservation zone 2 (the outer coast of Washington; 2012–2015); about 7,600 murrelets in conservation zone 3 (from Coos Bay north to the Columbia River, Oregon; 2011–2014); and about 6,600 birds in conservation zone 4 (from Shelter Cove, California, north to Coos Bay, Oregon; 2012–2015). The use of averages accounts for some of the annual variation in population estimates. Single-year estimates vary among years and tend to have relatively large confidence intervals. For example, the most recent estimate for conservation zone 2 (3,204 murrelets in 2015) is higher than the 4-year average, but with a 95 percent confidence interval (1,883 to 5,609) (Lynch et al. 2016) that includes that average. All annual estimates at the conservation zone and other scales are found in recent reports from the NWFP's murrelet effectiveness monitoring program (Falxa et al. 2016, Lynch et al. 2016).

Estimated density of murrelets on the surveyed waters (generally within 2 to 3 mi [3 to 5 km] of shore, depending on conservation zone) (Raphael et al. 2007) ranged from approximately 0.1 murrelets per square kilometer in conservation zone 5 to 7.5 murrelets per square kilometer in conservation zone 4 in 2015. Annual population estimates for the entire Plan area ranged from about 16,600 to 22,800 murrelets during the 15-year period (fig. 5-5), and averaged about 21,000 birds over the past 4 years (2011–2014); the most recent estimate for the Plan area is 21,300 birds for 2014 (95 percent confidence interval: 17,500 to 25,100) (Lynch et al. 2016). The confidence intervals associated with population estimates reflect the difficulties in sampling such a mobile, patchily distributed, and relatively rare species over a large area of ocean waters. Although this sampling error decreases the power to detect population trends, the trend estimation accounts for sampling error.

The estimates from population monitoring form the basis for evaluating population trends since 2000. The monitoring program evaluated linear trends from 2000 to 2015 at multiple scales (Lynch et al. 2016), and found evidence for a declining trend in Washington, no clear trend in Oregon, and evidence for an increasing trend in the California portion of the Plan area (fig. 5-6). In Washington (fig. 5-7), there was strong evidence of a population decline in conservation zone 1 (a 5.3 percent annual decline, 95 percent confidence interval: -8.4 to -2.0) (Lynch et al. 2016), and a 4.4 percent decline per year for Washington state (conservation zones 1 and 2 combined; 95 percent confidence interval: -6.8 to -1.9) (Lynch et al. 2016). In conservation zone 2, where past analyses found a declining trend (Falxa et al. 2016), the most recent trend analysis, with 2014 and 2015 data included, indicates that a negative trend may continue in conservation zone 2, but the upper confidence interval now overlaps zero (fig. 5-7), thus the trend for this zone is uncertain (95 percent confidence interval: -7.6 to 2.3) (Lynch et al. 2016). In conservation zones 3 and 5, the most recent data provide no evidence of a trend (confidence intervals broadly overlap zero) (Falxa et al. 2016, Lynch et al. 2016); for an earlier period, Strong (2003) described a decline for central Oregon, which includes part of zone 3. In zone 4, the trend estimate was positive (3.0 percent per year), and with the addition of 2015 survey data the trend estimate's 95 percent confidence interval does not include zero (0.4 to 5.6; fig. 5-7), evidence for a positive trend on average for the 2000 to 2015 period for this zone (Lynch et al. 2016). At the state scale for Oregon and California, which combines conservation zones and portions of conservation zones, there was no evidence of a trend in Oregon (fig. 5-6). For California, as for zone 4, the trend estimate was positive for 2000 to 2015 (3.8 percent per year) and the 95 percent confidence interval for that estimate (0.9 to 6.8) lies entirely above zero, suggesting an increasing population (fig. 5-6).

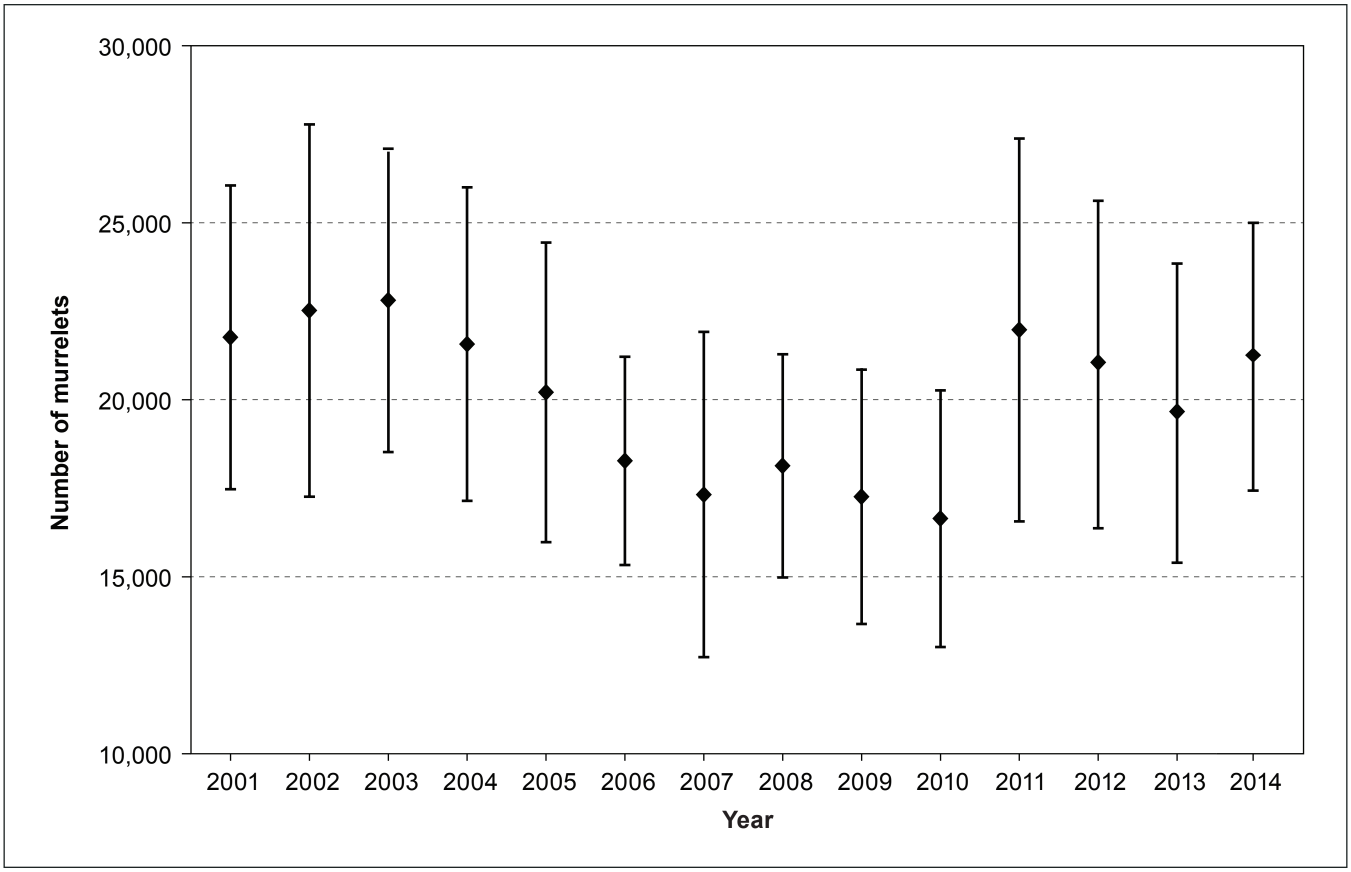

Figure 5-5—Annual marbled murrelet population estimates and 95 percent confidence intervals for the Northwest Forest Plan area (conservation zones 1 through 5 combined) based on 2000–2014 data (Falxa et al. 2016, Lynch et al. 2016).

For the entire Plan area, the estimated rate of population change for the 2001 to 2014 period was negative (-0.7 percent per year), but the confidence interval for the estimate (-2.3 to 0.8) broadly overlapped zero and there was no clear evidence for a trend (fig. 5-7). Additional years of monitoring should increase the power to detect an ongoing trend, such as where the trend is slight and power to detect low, but population trajectories can also change with time, which adds variability and difficulty in describing trends. For example, the magnitude and strength of evidence for a NWFP-wide population decline have decreased relative to a previous assessment for the 2001 to 2010 period (Miller et al. 2012). This difference may be driven by a variety of factors, most notable being the higher population estimates for 2011 through 2014 compared to the previous several years (fig. 5-5), which reduced the slope of the trend and increased variability (Falxa et al. 2016, Lynch et al. 2016). In 2011 and 2012, estimates of murrelet population size increased in all conservation zones except conservation zone 2, compared to estimates from previous years. Falxa et al. (2016) discuss and evaluate potential causes for the pattern observed, which include (1) change in the distribution of murrelets relative to shore that affects the proportion of the population sampled, (2) change in the model parameters used to estimate density, (3) shift of murrelets from nonsampled units to sampled units in conservation zone 1, (4) movement of birds into conservation zone 1 from the north or south during 2011 to 2013, and (5) potential effects of atypical timing of breeding or proportion of the population nesting. The cause(s) remain unknown, and continued monitoring and research should help managers better understand population trends and assess underlying factors that might explain trends and variability in annual estimates.

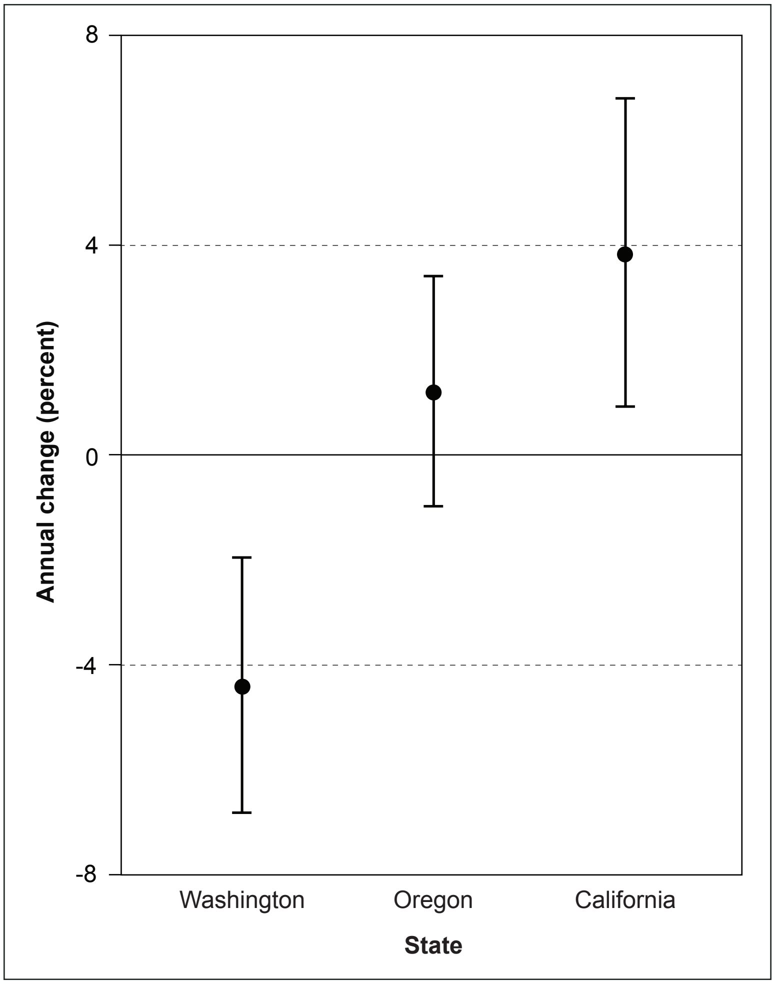

Figure 5-6—Trend results: average rate of annual change by state, 2000 to 2013, with 95 percent confidence intervals. Washington trend is based on 2001–2015 data, Oregon on 2000–2014 data, and California on 2000–2015 data (Falxa et al. 2016, Lynch et al. 2016).

The population monitoring results to date indicate that, as expected, the NWFP goal of stabilizing and increasing murrelet populations has not yet been achieved throughout the Plan area. Although the population monitoring data for 2000 through 2015 are not consistent with declining populations in Oregon and California during this period, murrelets are declining in Washington. The Washington trend results are consistent with demographic models for the murrelet (McShane et al. 2004, USFWS 1997), which predicted declining populations based on the available data on rates of murrelet survival and reproductive output. The population monitoring data suggest a north-to-south trend pattern, in which population trends appear to improve from north to south within the Plan area based on the last 15 years. The observed Oregon and California trend results are not consistent with model predictions. However, major sources of uncertainty include (1) uncertainty in estimating survivorship and fecundity (reproductive output) in the demographic models, (2) uncertainty about whether the murrelet populations being monitored are closed or open to immigration, and (3) the relatively large confidence intervals around population estimates. Murrelets occur immediately to the north of the Plan area, and monitored populations may be subsidized by immigrants from British Columbia or Alaska, where birds are more abundant (Falxa and Raphael 2016, Raphael 2006). Peery et al. (2007) found that immigration of murrelets from north of the zone 6 (Santa Cruz Mountains) population may have been sufficient to mask an intrinsic decline in the zone 6 population; this could occur elsewhere.

Status and trend of nesting habitat—
Whereas the focus of the murrelet effectiveness monitoring program is on the status and trends of murrelet populations and nesting habitat on federal lands within the Plan area, the populations monitored at sea respond to nesting habitat conditions on both federal and nonfederal lands. To better understand the murrelet's conservation status, and the relationship between population conditions and nesting habitat conditions, monitoring considered nesting habitat conditions across both federal and nonfederal lands (Raphael et al. 2016a). Also, in some areas, such as southwest Washington and northwest California, few federal lands occur within the murrelet's nesting range, and thus nonfederal lands are likely important to murrelet conservation.

***Baseline nesting habitat*—**When the NWFP was developed, no consistent map of murrelet nesting habitat was available. For purposes of the Plan, murrelet nesting habitat was then assumed to be late-successional forest with much

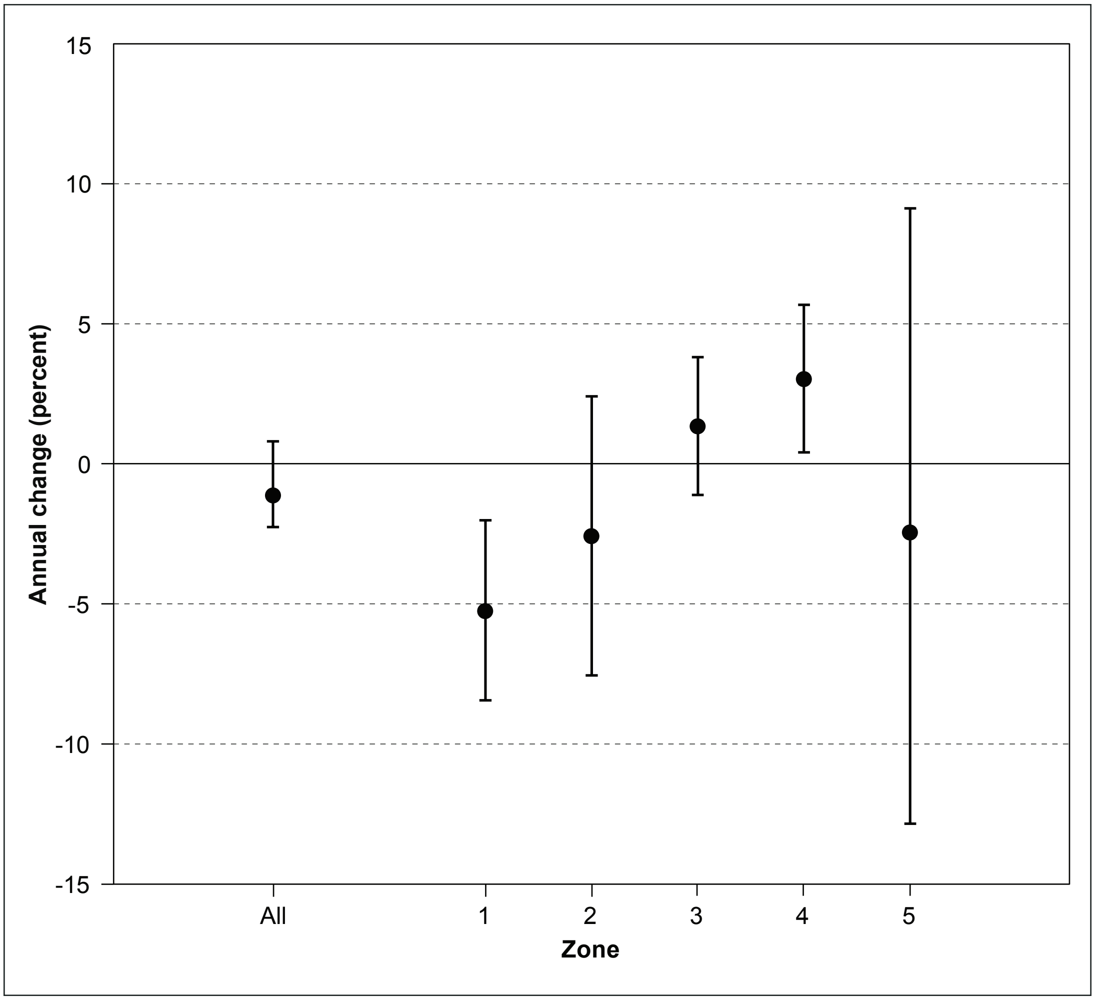

Figure 5-7—Trend results: average rate of annual change by conservation zone (see fig. 5-2 for zone locations) and for all conservation zones combined, with 95 percent confidence intervals. All zones based on 2001–2014 data, zones 1 and 2 on 2001–2015 data, zone 3 on 2000–2014 data, zone 4 on 2000–2015 data, and zone 5 on 2000–2013 data (Falxa et al. 2016, Lynch et al. 2016).

the same characteristics as northern spotted owl habitat. Therefore, the existing map of spotted owl habitat, which was itself a mosaic derived from compilations of local maps based on agency judgment, classified satellite imagery, and existing inventory maps, was constrained to the range of the murrelet and used as a proxy for murrelet nesting habitat. No estimate or map of nesting habitat on nonfederal land was available. The murrelet effectiveness monitoring group has since developed a series of maps, using a consistent vegetation base across all ownerships throughout the Plan area (Raphael et al. 2016a); the maps were based first on vegetation data from CALVEG and the Interagency Vegetation Mapping Project (Moeur et al. 2005), and then later based on Gradient Nearest Neighbor (GNN) vegetation data (Davis et al. 2015, Ohmann and Gregory 2002, Moeur et al. 2011).

The primary objectives of the effectiveness monitoring plan for the murrelet included mapping baseline nesting habitat (at the start of the NWFP in 1993) and estimating changes in that forest over time. For the NWFP 20-year analysis and report, Raphael et al. (2016a) used maximum entropy (Maxent) models to estimate nesting habitat suitability over all habitat-capable lands in the murrelet's range in Washington, Oregon, and California. "Habitat-capable" lands were defined as lands capable of supporting or developing into murrelet nesting habitat (fig. 5-8). The area of habitat-capable lands evaluated by the 20-year analysis included about 20.7 million ac (8.5 million ha) of federal plus nonfederal lands within the murrelet range portion of the Plan area (Raphael et al. 2016a).[3]

The portion of the murrelet range included in this analysis excluded inland zone 2 of Oregon and California, where no murrelet nests have been observed (see Raphael et al. 2016a for details). The models used vegetation and climate attributes, and a sample of 368 murrelet nest sites (184 confirmed murrelet nest sites and 184 occupied sites) for model training. Occupied sites are sites where murrelet behaviors associated with nesting have been observed during carefully prescribed surveys (Evans Mack et al. 2003); such sites do not have confirmed nests but are places deemed likely to have nests. Attributes used to build the model included estimates of canopy cover, mean tree diameter, diameter diversity, canopy layers, number of nesting platforms, stand age and stand height, an index of old-growth structure, percentage of a 124-ac (50-ha) area composed of older forest, and several climate variables. All of these attributes were derived from a regional vegetation database and a climate database that covered the entire Plan area as described in Raphael et al. (2016a). The model classified each 30-m pixel in the Plan area with a nesting habitat suitability score ranging from 0 (unsuitable) to 1.0 (most suitable); higher scores indicate that a pixel has vegetation and climate characteristics more similar to those in the sample of murrelet nest sites, compared to a random sample of available forest. Model validation was accomplished by withholding 25 percent of the training data, testing the model on the withheld data, and replicating the process 25 times.

Thresholds were defined that summarized land area into four classes of nesting habitat suitability; classes 1 and 2 were deemed lower suitability, and classes 3 and 4 were deemed higher suitability (see Raphael et al. [2016a] for a detailed explanation of these suitability classes and the cutoff values used to define them). The model was run 25 times for each state and then summarized to provide an estimate of model error, owing to variation in model runs themselves and variation in underlying GNN data. Raphael et al. (2016a) estimated that there were 2.53 million ac (1.02 million ha) of higher suitability nesting habitat over all lands in the murrelet's range in Washington, Oregon, and California at the start of the NWFP; this included 1.50 million ac (0.61 million ha) on federal lands. Of the 2.53 million ac of higher suitability nesting habitat, 0.46 million ac (0.18 million ha) were identified as highest suitability (class 4), matching or exceeding the average conditions for the training sites; of this, 0.25 (0.10 million ha) million ac were on federal lands. A substantial amount (41 percent) of baseline nesting habitat occurred on nonfederal land (fig. 5-9). The estimate of nesting habitat on federal land from the 1993 final supplemental environmental impact statement was 2.6 million ac. Differences between the 1993 and current nesting habitat estimates were to be expected, as the new map was derived from a nesting habitat suitability model specific to the murrelet, and was built from forest- and satellite-derived data that had not been available at the time the NWFP was written. As noted earlier, the final 1993 supplemental environmental impact statement used habitat for the northern spotted owl as a proxy for murrelet nesting habitat.

Although a substantial amount of higher suitability nesting habitat occurred on nonfederal lands, federal lands contributed proportionately more suitable nesting habitat. Of the about 20.7 million ac (8.4 million ha) of forest land capable of supporting or developing into murrelet nesting habitat, federal lands comprise only about 28 percent of the area, but provided 59 percent of the suitable nesting habitat at the start of the NWFP (Raphael et al. 2016a). The contribution of suitable nesting habitat from nonfederal land varies: in Washington, 42 percent; in Oregon, 33 percent; and in California, 80 percent (fig. 5-9). On the 1.0 million ac (0.4 million ha) of suitable nesting habitat on nonfederal lands in 1993, about 39 percent was managed by states. In Washington, the proportion of the nesting habitat on federal lands that is within reserves is 93 percent; in Oregon, 88 percent; and in California, 93 percent. The final supplemental environmental impact statement estimated that 86 percent of murrelet nesting habitat on federal lands

[3] Does not include conservation zone 6, which is south of San Francisco and outside of the NWFP area.

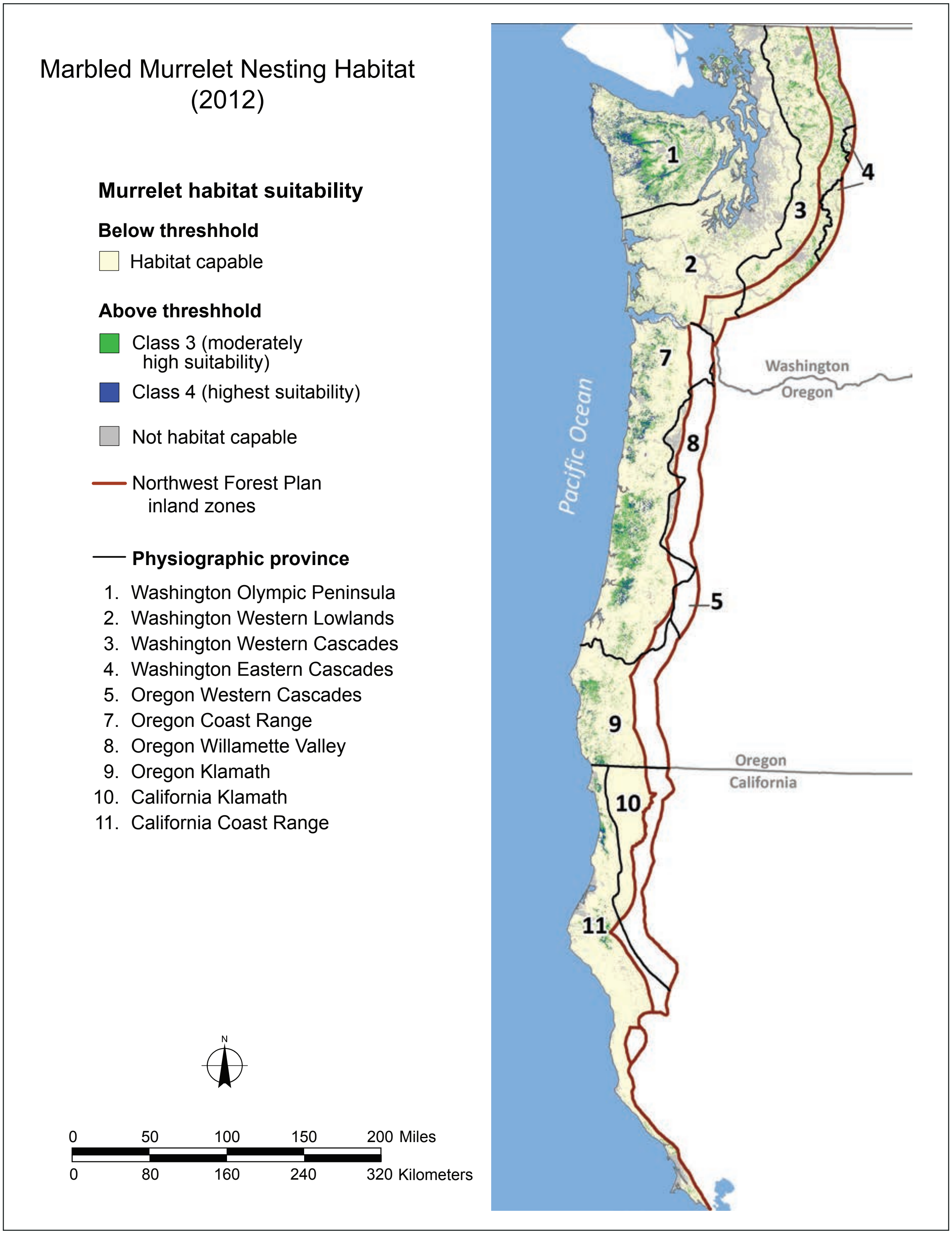

Figure 5-8—Map of suitability for marbled murrelet nesting habitat, 2012 (Raphael et al. 2016a).

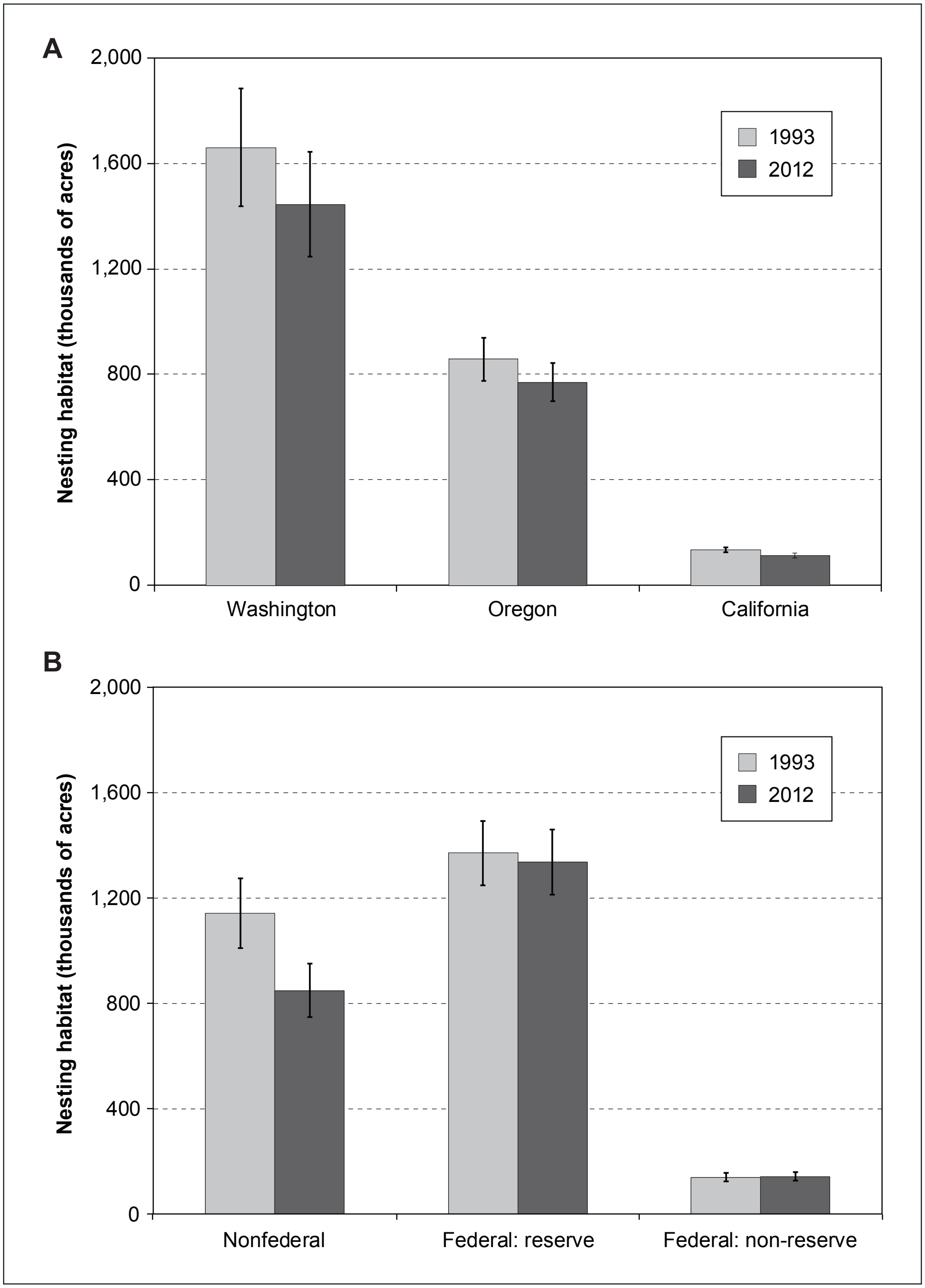

Figure 5-9—Estimated amounts of higher suitability nesting habitat of the marbled murrelet in 1993 and 2012, by (A) state, and (B) land allocation (Raphael et al. 2016a). Error bars are 95-percent confidence intervals from 25 replicated model runs. See table on page 338 for metric equivelents.

would be in reserves. The 20-year analysis found that, in 1993, 90 percent of potential nesting habitat on federally administered lands occurred within reserved-land allocations (Raphael et al. 2016a). Thus, the NWFP seems to have successfully captured most of the existing higher suitability nesting habitat on federal lands within its reserve system. We conclude that the NWFP had successfully encompassed a majority of murrelet nesting habitat within its reserve system but that a substantial amount of additional suitable nesting habitat occurs on nonfederal lands over which the NWFP has little or no control.

***Nesting habitat losses*—**The intent of the NWFP is to conserve most of the remaining murrelet nesting habitat and to prevent the subsequent loss of any nesting habitat occupied by nesting birds, wherever that nesting habitat occurred on federal lands. The amount of nesting habitat was expected to increase over time, but the rate of increase would be very slow, and changes might not be observed for many decades. In the meantime, some unoccupied nesting habitat would be lost to timber harvest on federal land, and some losses might be caused by wildfire and other disturbances.

The observed trends are in line with these expectations. Raphael et al. (2016a) used satellite imagery and change detection methods (see Davis et al. 2015) to estimate a net loss of 307,957 ac (124,692 ha) of higher suitability nesting habitat over all lands (including nonfederal) from 1993 to 2012, or a total loss of about 12 percent. Net loss was about 27 percent from the baseline on nonfederal lands, and 2.2 percent on federal lands (table 5-2). Of those losses on nonfederal lands, the highest rate of loss was on private lands (37 percent); losses on state lands were just under 10 percent (table 5-2). Of those losses on federal lands, 62 percent was due to fire (most of that in one event, the 2002 Biscuit Fire); 23 percent to timber harvest; and 16 percent to insects, disease, or other natural disturbances (table 5-3). On nonfederal lands, 98 percent of losses were due to timber harvest, and 2 percent to insects, disease, and other causes (table 5-3).

Table 5-2—Change in acres (thousands) of suitable nesting habitat from 1993 to 2012 by land ownership in the Northwest Forest Plan area (updated from Raphael et al. 2016a)

State	Owner	1993	2012	Change
		- - - - - - *Acres (thousands)*	*- - - - - -*	*Percent*
Washington	Federal	899.7	887.1	-1.4
	State	243.7	209.7	-29.8
	Other nonfederal	405.6	246.3	-39.3
Oregon	Federal	573.1	553.7	-3.4
	State	123.3	119.6	-3.0
	Other nonfederal	157.0	101.5	-35.4
California	Federal	26.5	26.0	-1.9
	State	32.3	31.9	-1.2
	Other nonfederal	73.7	51.3	-30.4
Plan area total	Federal	1,499.3	1,466.8	-2.2
	State	399.2	361.2	-9.5
	Other nonfederal	636.4	398.8	-37.3

Note: see table on page 338 for metric equivelents.

Table 5-3—Attribution of loss, in thousands of acres, of marbled murrelet higher suitability habitat from the Northwest Forest Plan baseline (1993) to 2012 by land allocation

	Losses[a]			
Land allocation	**Fire**	**Harvest**	**Other**	**Total**
	Acres (thousands)			
Federal reserved	19.1	4.6	5.3	34.8
Federal nonreserved	2.4	3.3	0.2	5.3
Nonfederal	0.6	308.7	6.9	316.3
Total	22.1	316.7	12.4	351.7

[a] Losses as verified by LandTrendR (see Raphael et al. 2016a for details).
Source: Raphael et al. 2016a.

***Nesting habitat increases*—**One NWFP expectation was a gradual increase in the amount of suitable nesting habitat as forests mature. Previous evidence showed that the amount of forest with large (>20 [>51 cm] inches in diameter) trees had increased by about 15 percent over the first 10 years of the NWFP, based on analyses of inventory plots on national forest lands (Moeur et al. 2005). More recent work, however, showed a decrease of about 2.8 percent in the amount of older forest on federal lands and about 6 percent over all lands within the entire NWFP area; the discrepancy may be due to the newer definitions of older forest used in the more recent estimates (Davis et al. 2015); this analysis included large areas outside (inland to the east) of the murrelet nesting range. As noted above, net losses of murrelet nesting habitat totaled about 12 percent over all lands and 2.2 percent on federal lands. At some point in the future, the extent of current young forest within the reserve system on federal land will be such that we could see a net increase in amount of suitable nesting habitat. For example, trends in the Oregon Coast Range on federal lands show that nesting habitat can increase when stand-replacement rates of disturbance are low and forest age classes are available to grow into murrelet nesting habitat in a few decades. Unfortunately, however, we are unaware of any estimates of exactly when that point will be reached. There is a need to develop models to project forest conditions forward in time and to then estimate future nesting habitat suitability. We do know, as pointed out in Raphael et al. (2016a), that there is sufficient young and mature forest within the reserve system (fig. 5-8) to eventually make up for losses since the start of the NWFP, if future nesting habitat losses on federal lands remain similar to the first 20 years of the NWFP, and the NWFP reserve system remains intact and continues to be managed for the development of old-forest conditions. While at broader scales the amount of murrelet nesting habitat declined, some gains in nesting habitat may already be occurring locally, notably on Forest Service lands in the Oregon Coast Range province, where small net gains (about 1 percent) were observed by the 20-year analysis (Raphael et al. 2016a).

Status of Marbled Murrelets Elsewhere in the Species' Range

The NWFP effectiveness monitoring program provides data on murrelet status and trends that is unparalleled elsewhere in geographic and temporal extent. Nonetheless, other monitoring programs exist elsewhere within the species' range (see fig. 5-3 for range map); these provide information on the status and trends for some areas outside of the NWFP area. The most comprehensive of these in geographic scope is conducted by the Canadian government to assess temporal trends of the murrelet in British Columbia. That program recently reported on murrelet population trends from 1996 through 2013, based on a radar-based monitoring program; they found evidence for a coastwide decline of about 1.6 percent per year in British Columbia (Bertram et al. 2015a). Trends varied strongly among the six sampling regions within British Columbia: negative trends were detected in their east Vancouver Island (-9 percent per year) and south mainland coast (-3 percent per year) regions, and a weak negative trend in Haida Gwaii. A separate program has monitored at-sea murrelet numbers from about 62 mi (100 km) of transects on the southwest coast of Vancouver Island during May to July since 1995. Results from this effort suggest an initial decline through 2006, followed by stable or increasing numbers since 2006 (Bertram et al. 2015a; Zharikov et al. in Irvine and Crawford 2012; Y. Zharikov, pers. comm.[4]). The most recent

[4] **Zharikov, Y. 2016.** Personal communication. Monitoring ecologist, Parks Canada, Ucluelet, BC V0R 3A0.

population estimate in British Columbia, using extrapolations from at-sea surveys and radar counts, gives the range as 72,600 to 125,600 birds of all ages (mid-point 99,100 birds) (COSEWIC 2012).

In central California, the small murrelet population of conservation zone 6 (from the mouth of San Francisco Bay to Point Sur in Monterey County) has been monitored with at-sea surveys almost annually since 1999. Those surveys estimated population sizes of about 400 to 600 birds between 2009 and 2014 (Henry and Tyler 2014), with no clear trend during that period, but an apparent decline compared to numbers from 1999 to 2003 (Henry et al. 2012).

Data are more limited on the murrelet's status in Alaska, where its range extends from the southeast corner of the state through the Aleutian Islands. Within that area, monitoring surveys have been conducted annually in Glacier Bay since 2009; murrelet numbers there have been variable, with the highest annual estimates in 2013 and 2015 (Sergeant et al. 2015). Monitoring surveys throughout Prince William Sound in 11 years between 1972 and 2007 suggest that murrelet abundance there declined by an annual average rate of about 4 to 5 percent per year for that period (Kuletz et al. 2011).

Less recent information is available from a 2007 evaluation of the status of the murrelet in Alaska and British Columbia (Piatt et al. 2007). That review evaluated trends for Alaska using at-sea survey data from eight different and widely distributed sample sites. Although the sites differed in methods, sampling effort, and time period sampled, the evaluation found evidence for significant declines at five of eight sites, at annual rates of -5.4 to -12.7 percent since the early 1990s (Piatt et al. 2007). While acknowledging uncertainty resulting from a lack of recent survey data from key areas, they projected the 2007 murrelet population in Alaska to be roughly 270,000 birds, representing a decline of about 70 percent over a 25-year period (Piatt et al. 2007). They concluded that the declines were likely real, and attributed them to combined and cumulative effects from climate-related changes in the marine ecosystem affecting prey resources (including a regime shift in the Gulf of Alaska that reduced the abundance of important murrelet prey), and human activities (logging, gill net bycatch, and oil pollution).

As noted below, Raphael et al. (2016b) reported a correlation between numbers of murrelets counted at sea and amounts of adjacent suitable nesting habitat within the three-state region of the NWFP. This relationship, however, seems to vary considerably in different portions of the murrelet range, as illustrated in table 5-4. Certainly, part of the reason for this variation is due to differences in methods and definitions of nesting habitat, but the magnitude of difference (e.g., 207 ac [84 ha] per bird in Washington versus 15 ac per bird in Alaska) suggests that there are real differences in relationships between offshore numbers of birds and inland nesting habitat in the various regions. We note that there is likely a higher proportion of murrelets in Alaska nesting in small patches of forest, which are likely to be excluded in forest inventories, and on cliffs or on the ground (Barbaree et al. 2014). It is also possible that foraging prey density is much greater in Alaska, supporting a larger number of birds relative to available nesting habitat compared with other parts of the range.

Table 5-4—Estimated amounts of potential nesting habitat (rounded to nearest 100 ac), murrelet population size, and ratio of habitat to population in portions of the murrelet range (as depicted in fig. 5-7)

Region	Nesting habitat	Estimated murrelet population	Habitat area per bird	Source
	Acres		*Acres*	
Southeast Alaska	2,034,700	144,200	15	Piatt et al. 2007
British Columbia	3,439,100	99,100	35	Environment Canada 2014
Washington	1,549,000	7,494	207	Lynch et al. 2016, Raphael et al. 2016a
Oregon	853,400	11,384	75	Lynch et al. 2016, Raphael et al. 2016a
California	132,600	5,666	23	Lynch et al. 2016, Raphael et al. 2016a

Nesting Habitat Relationships

Patches and edges—

Although the behavior and habitat cues used by murrelets to locate nest sites are not known, their nests tend to be widely spaced across the landscape, especially if there is extensive suitable nesting habitat (Nelson 1997). In areas where there is a wide choice of suitable trees, nest trees tend not to be re-used in successive seasons (Burger et al. 2009). Nests located using radiotelemetry in Desolation and Clayoquot Sounds, British Columbia, had mean inter-nest distances of 2.9 ± 2.5 (standard deviation [SD]) mi (4.6 ± 4.0 km) and 4.1 ± 2.6 mi (6.6 ± 4.2 km), respectively, although there were, almost certainly, undiscovered nests in between. Other telemetry studies showed similar wide spacing (Barbaree et al. 2014, Bloxton and Raphael 2009, Wilk et al. 2016), although in northern California where nesting habitat is very limited, nests were closer together and more often reused (Hébert and Golightly 2006). In some circumstances, nests might be more closely aggregated. For example, on the southern mainland coast of British Columbia, Manley (1999) found that 52 percent of nests located with tree climbing were within 300 ft of another nest, and on Naked Island, Alaska, Naslund et al. (1995) found three nests within a 43-ac (19 ha) stand. Additional evidence of co-location within stands and watersheds is reviewed by Plissner et al. (2015).

Analyzing the distribution of marbled murrelet nests relative to patch size and forest edges is limited, because many studies lacked a statistical comparison of habitat use in patches or edges versus the availability of these and alternative habitats (Jones 2001), and proximity to edges was not considered in relation to the degree of fragmentation of the landscape. Marbled murrelets are known to nest within 150 ft (46 m) of forest edges and in small, often isolated patches of suitable trees. The data summarized by McShane et al. (2004) showed that 75 percent of all nests were within 164 ft (50 m) of forest edges. Most of these edges were natural edges (streams, wetlands, natural forest gaps, and avalanche chutes) but almost a third of all nests were close to edges created by human activities. These data include nests located from ground searches and tree climbing linked to audiovisual surveys, and these nests are likely to be biased toward being found near edges (Burger 2002). When considering only the nests found by climbing randomly selected trees and radiotelemetry to remove possible bias, the results were similar: most nests were located near edges (76 percent of 152 nests), and the most common type of edge was natural (69 percent of 115 edge nests) (McShane et al. 2004). In this unbiased sample, which covered a range of modified and relatively pristine nesting habitats in Oregon, Washington, and British Columbia, 24 percent of all nests were near manmade edges, even though interior forest existed near many of these nests. Distances of nests to all edges in these samples ranged from 20 to 2,100 ft (6 to 640 m), and proximity to anthropogenic edges ranged from 9 to 1,000 ft (3 to 305 m) (McShane et al. 2004).

Studies using telemetry in British Columbia and Alaska found some murrelets nesting in small, often isolated patches of suitable forest; these patches were usually in higher elevation sites, where suitable trees are sparse and small patches of larger trees provide suitable platforms (e.g., Barbaree et al. 2014, Bradley 2002). When small patches are used in lower elevation sites, this often occurred where logging had removed most of the low-elevation suitable forest (e.g., Zharikov et al. 2006, 2007a). It is possible that murrelets persisted in such small patches because of site fidelity. Murrelets have shown a strong fidelity to sites where they have previously nested (e.g., Hébert and Golightly 2006). It is important to note that nest success may be lower in these smaller patches, probably because of higher risk of nest depredation (Barbaree et al. 2104). Fine-scale spatial analysis of the nests found with telemetry in Desolation Sound, on the southern mainland of British Columbia, showed that murrelets were more likely to nest close to natural edges, but there were insufficient data to test whether this was true for manmade edges (Burger 2002).

Two studies of nest placement did consider the use versus availability of edge habitat and patch size within the landscape. Raphael et al. (2016a) found that more than 60 percent of 162 nests in Washington, Oregon, and California were found in interior forest (defined as further than 180 ft (55 m) from any edge) (table 5-5). In that study, only 23 percent of potential nesting habitat occurred as interior forest on all lands in the study area, indicating a greater-than-expected occurrence of nests in interior forest. Wilk et al. (2016) analyzed nesting habitat at nests used by birds

Table 5-5—Number of marbled murrelet nests[a] located in core areas (interior forest) and near (within 180 ft [55 m]) edges

Location	Core	Core edge[b]	Edge[c]	Total
Washington	24	15	8	47
Oregon	29	23	4	56
California	45	8	6	59
Total	98	46	18	162
Percent	61	28	11	
Available (percent)[d]	22	28	49	

[a] Numbers of nests as sampled in Raphael et al (2016a), not the total number of known nests in this region.
[b] Edge of interior forest (core) patch.
[c] Isolated edge or stringer.
[d] Percentage of each type throughout range.
Source: Raphael et al. 2016a.

tagged with radios in the waters close to the Olympic Peninsula, Washington. Murrelet nests in Washington (n = 18) had greater core areas of older forest than random sites (235 ac [95 ha] at nest sites versus 25 ac [10 ha] in random sites). Core area is the interior area of the forest patch after buffering edge effects (180-ft buffers); this measure integrates patch size, shape, and edge-effect distance into a single measure. Raphael et al. (2016a) also found that patch cohesion, the physical connectedness of the corresponding patch type (index range 0 to 100), was greater at nests than random sites (93 at nests, 66 at random sites). They concluded that stands with nests were less fragmented than available forest across the murrelet's range that they sampled.

Edge effects on forest nesting habitat: windthrow, microclimate, and epiphytes—
A general rule of thumb used in Pacific Northwest forests has been that microclimatic effects penetrate two tree heights (240 to 300 ft [73 to 93 m]) and sometimes farther (450 ft [137 m] or more) into old-growth forests bordering clearcuts or similar sharp-gradient boundaries (Franklin and Forman 1987, Kremsater and Bunnell 1999). This is supported by some field studies, but local variables like topography, wind exposure, type of forest, and the surrounding matrix strongly influence the magnitude and influence distance of these edge effects (reviewed below).

Several studies reviewed below found differences based on edge type, in which "hard" edges are those with recent clearcuts (e.g., 0 to 20 years old) and "soft" edges are with regenerating forest (such as 21 to 100+ years old).

Windthrow refers to the uprooting or breakage of trees by wind, which can affect murrelets owing to loss of potential nest trees and nest limbs. Windthrow is increased when clearcuts, and to a lesser extent roads, increase the exposure of residual trees to wind (Sinton et al. 2000). Windthrow and physical damage to canopy branches are common problems at hard edges within the murrelet's range. In the Pacific Northwest, factors affecting the risk and degree of windthrow include orientation relative to winter winds; topography; the age, height, and density of trees; soil type; exposure to wind prior to logging (trees exposed to winds are more likely to develop stronger root systems); and the shape and size of the clearcuts and residual stands (Franklin and Forman 1987, Gratowski 1956, Mitchell et al. 2001). Although local factors have a strong influence, these impacts are generally found within 150 to 240 ft (46 to 73 m of edges, are most prevalent in patches less than 3 ha (7.4 ac), and are most likely within 25 years of clearcut logging creating the edges. In a review of data from the Pacific Northwest, Franklin and Forman (1987) suggested that wind-driven edge effects were likely to penetrate into remnant forests about two tree heights (240 ft [73 m]) from clearcut edges, but they did not distinguish between windthrow, canopy damage, and changes to microclimate.

Canopy epiphytes (mostly mosses) provide nest platforms for murrelets in much of the NWFP area. Exposure to increased wind and solar radiation at newly created edges could be detrimental (through wind-removal, thermal stress, and desiccation) or beneficial (through increased light for photosynthesis) to these epiphytes. Studies in the Pacific Northwest found variable effects of edges on bryophytes, although moss cover tended to be lower near hard edges. Local features, especially topography, time since edge creation, edge orientation, aspect, the nature of the surrounding harvested matrix, and even soil conditions have a strong effect on physical damage and changes in edge microclimates (Franklin and Forman 1987, Gratowski 1956, Mitchell et al. 2001, Muth and Bazzaz 2002, Sherich et al. 2013). These studies of edge effects on epiphytes and microclimate, although not focused on murrelet nesting, indicate that in many cases forests within 150 ft (46 m) of hard edges are likely to provide adverse conditions for nesting murrelets, and in situations with greater wind exposure, these adverse conditions could extend well beyond 300 ft (91 m). These adverse conditions are likely to diminish as the adjacent regenerating forest reduces the edge gradient (i.e., creates "soft" edges). One study, by Van Rooyen et al. (2011) at four locations in British Columbia, has specifically investigated edge effects on factors relevant to nesting murrelets. Compared to adjacent interior forest, epiphyte cover on canopy branches was slightly lower at hard edges (possibly because of the microclimate effects discussed above), about the same at soft edges, and slightly higher at natural edges. There was a large difference in the density of trees with potential nest platforms between hard edges and forest interiors (1.5 versus 6.4 platform trees per acre [0.6 versus 2.6 per hectare]); the difference was less marked at soft edges (6.5 versus 10.8 platform trees per acre [2.6 versus 4.4 per hectare]) and negligible at natural edges. The authors concluded that the creation of artificial edges by forest fragmentation would have negative consequences for epiphytic development for 20 to 30 years, and this might reduce nesting habitat for murrelets.

Natural forest edges bordering openings produced by streams, avalanche chutes, and wetlands generally do not provide adverse conditions for nesting murrelets, and if temperature and moisture regimes are favorable, such edges might be more suitable for murrelets than interior forests (Harper et al. 2005, Van Rooyen et al. 2011). Despite the evidence of negative microclimates and bryophyte development near hard edges, murrelet nests have been observed within 150 ft (46 m) of such edges, suggesting that conditions there are not always an absolute deterrent to the birds. We do not know if they avoid hard edges, i.e., whether nest densities at hard edges are lower than those elsewhere in old-growth forests. On balance, however, the evidence suggests that the creation of small patches and hard edges can be detrimental in areas where maintenance of nesting murrelets is a priority. Occurrence of nests along edges may, as noted above, be a result of site fidelity and a tendency to nest at previously used locations even when disturbances have created edges near those sites.

Microclimates within old-growth forests differ from those in clearcuts or young regenerating forests. In general, extremes of temperature and solar radiation are minimized, and humidity in summer is higher and more stable in old-growth forests than in recent clearcuts (Chen et al. 1999, Frey et al. 2016). Changes in microclimates can have both direct and indirect effects on nesting murrelets. Direct effects include thermal stress (both hot and cold) and dehydration if adults or chicks are exposed to direct sunlight or increased winds. Indirect effects are most likely to occur through changes to the availability of moss pads and other epiphyte growth on which most murrelet nests have been found.

Analysis across the Plan area indicates that the prevalence of fog is a strong contributor to predictive models of suitable nesting habitat for murrelets (Raphael et al. 2016a). In areas where fog is frequent, it might mitigate some edge effects, by promoting epiphyte growth and ameliorating stressful solar radiation. However, there is some evidence of reduced fog frequency, at least in California, over the past century (Johnstone and Dawson 2010).

Landscape-level relationships between nesting habitat and populations—

***Data from radar surveys*—**In this section, a landscape-level spatial scale considers entire watersheds and similar large areas in contrast to smaller stand- and patch-level analyses. Counts of murrelets entering watersheds obtained by detections from radar equipment have been instrumental in showing that murrelet numbers are strongly correlated with available areas of suitable old-growth nesting habitat (Burger 2001, Burger et al. 2004, Raphael et al. 2002a). In addition, Raphael et al. (2002a) also tested for the effects of habitat fragmentation in watersheds sampled with radar on the Olympic Peninsula, Washington. In their 3-year study, numbers of murrelets detected increased as the amount of core-area old-growth (defined as interior forest more than 300 ft [92 m] from an edge) increased ($r^2 = 0.69$, 0.82, and 0.76 in 1998, 1999, and 2000, respectively, $p < 0.01$), but decreased with increasing amounts of edge in late-seral patches. Numbers of murrelets were not correlated with patch density (number of patches per hectare), mean patch size, or spacing (proximity) of late-seral patches, nor with the overall diversity of all forest cover types within the landscape.

Cortese (2011) compared radar counts of murrelets entering watersheds with forest cover parameters within these watersheds in three regions of British Columbia: southwest Vancouver Island, and the central and southern mainland coasts. One goal of the study was to investigate the effects of forest fragmentation within these watersheds. As expected from previous radar studies (Burger 2001, Burger et al. 2004, Raphael et al. 2002a), total area of old-growth forest was included in the top predictive models for all three regions, which explained 11 to 35 percent of the variability in radar counts. Measures of mature forest edge density (including "hard" edges with clearcuts 0 to 20 years old, and "soft" edges with regenerating forest 21 to 140 years old) also were included in most predictive models, but there were marked regional differences in whether these were positive or negative associations. In the central and southern mainland coast regions, hard edges had a positive association with murrelet numbers, although there was high uncertainty in the model selection for the latter region. Cortese (2011), following Zharikov et al. (2006, 2007a), attributed this result to the preference by murrelets and the logging companies for the same patches of old-growth forest. Much of the old-growth forest in the watersheds studied in these regions has already been removed (Zharikov et al. 2006), and therefore murrelets tend to nest in the remaining forests where there is active logging and hence fragmentation. By contrast, murrelets in southwestern Vancouver Island, where a greater proportion of murrelet nesting habitat remains, showed a negative association with the density of hard edges and a strong negative association with the density of soft edges, and these edge factors were more important predictors in this region than in the other two regions (Cortese 2011).

***Data from at-sea surveys*—**Comparison of murrelet counts at sea with forest nesting habitat parameters emphasizes the value of tracts of suitable old-growth forest close to marine foraging areas (e.g., Falxa and Raphael 2016, Miller et al. 2002, Ronconi 2008, Raphael et al. 2015). In addition to the total area of accessible nesting habitat, Miller et al. (2002) found that nesting habitat patch size ($r = 0.91$) and contiguity of old-growth forest ($r = 0.95$) were the strongest predictors of murrelet densities at sea in northern California and southern Oregon. Raphael et al. (2016b) analyzed 13 years of data (2000–2012) from marine surveys in nine geographic strata across three states (Washington, Oregon, and California). Murrelet abundance at sea was most strongly correlated with the amount of higher suitability nesting habitat in the adjacent terrestrial environment ($r^2 = 0.324$), but there was considerable variance that was not explained by the factors included in the analysis. In addition, cohesion (an index of nesting habitat pattern in which higher values indicate more contiguous and less fragmented nesting habitat) was strongly and positively correlated ($r^2 = 0.76$) with murrelet abundance within the survey strata. We note, however, that amount of nesting habitat and cohesion of that habitat cannot be considered independent; cohesion tends to increase as amount of nesting habitat increases. Although the unexplained variance indicates that other factors also influence murrelet distribution and abundance, the results of Miller et al. (2002) and Raphael et al. (2015, 2016b) indicate that fragmentation of nesting habitat has negatively affected murrelet populations across the large, diverse, and highly modified NWFP area.

***Nesting habitat configuration and risk of nest predation*—**Breeding success in murrelets tends to be low (typically less than 35 percent of nests fledge chicks). A study using museum specimens indicated that historical breeding success about a century ago was sufficient to maintain stable murrelet populations, but that contemporary reproductive success is not (Beissinger and Peery 2007). Predation is the highest known cause of nest failure in recent decades and is likely to limit murrelet populations in many areas. Corvids (crows, ravens, and jays) are the nest predators most commonly documented, but owls, diurnal raptors, and arboreal mammals (squirrels and mice) (Bradley et al. 2003; Malt and Lank 2007, 2009) are also likely to be important predators. Although definitive demographic studies testing the effects of predation are limited to the edge of the species range in central California (Peery and Henry 2010; Peery et al. 2004, 2006a), those studies and cumulative evidence from across the species range indicate that nest predation is a limiting factor on murrelet populations (McShane et al. 2004, Nelson and Hamer 1995, Piatt et al. 2007). Studies in several parts of the species range show that only about a third of murrelet nests result in fledging, e.g., 0.33 fledglings per nesting attempt rangewide, n = 124 nests (McShane et al. 2004), and 0.23 to 0.46 in British Columbia (Burger 2002). Research using radiotelemetry found failure rates of 54 percent in British Columbia (Bradley 2002), 68 to 86 percent in northern California (Hébert and Golightly 2006), 84 to 100 percent in central California (Peery et al. 2004), 80 percent in southeast Alaska (Barbaree et al. 2014), and 31 percent in south-central Alaska (Kissling et al. 2015). It is possible that nesting success results from radiotelemetry studies are affected by the method: Peery et al. (2006b) found that radio-tagged murrelets had a lower survival rate, and Ackerman et al. (2004) found that radio-tagging reduced reproductive success in another small alcid, the Cassin's auklet *(Ptychoramphus aleuticus*).

Predation is the greatest known cause of failure at 78 percent, or 29 of 37 nests with known outcomes in a rangewide analysis (McShane et al. 2004). In southern British Columbia, Malt and Lank (2007) found no difference between the survival of 57 actual versus 40 artificial murrelet nests and were able to document predator discovery at 40 percent of 136 artificial nests. In northern California, Hébert and Golightly (2006, 2007) attributed a minimum of 51 percent of nest failures across 3 years to predation, and documented egg predation by ravens (*Corvus corax*) and Stellar's jays (*Cyanocitta stelleri*). In central California, rates of nest predation were consistently high (67 to 81 percent)(Peery et al. 2004).

Several studies across the southern part of the murrelet's range have investigated nest success relative to forest edges and habitat fragmentation (table 5-6). As in many studies of habitat fragmentation, separating the effects of proximity to edge to the related effects of patch size and habitat configuration is often difficult (Harper et al. 2005, Lindenmayer and Fischer 2007). Nelson and Hamer (1995) found that successful nests were significantly further from forest edges (mean 510 ± SE 241 ft [155 ± 73 m], n = 9) than nests that failed (mean 90 ± SE 20 ft [27 ± 6 m], n = 8), and all successful nests, except one, were more than 180 ft (55 m) from the forest edge. For 58 nests with known locations from Oregon and British Columbia, Manley and Nelson (1999) (see also Burger 2002) reported that the success of nests within 150 ft (46 m) of a forest edge was 38 percent (n = 29) and for those more than 150 ft from an edge, success was 55 percent (n = 29), but this difference is not statistically significant. Successful nests were significantly further from edges (mean 462 ft [141]) than failed nests (mean 184 ft [56 m]). Predation was responsible for the failure of 60 percent of all active nests in these samples, and predation rates were higher within 150 ft of edges than farther into the forest interior. All 13 nests that were more than 450 ft (137 m) from an edge were successful or failed from reasons other than predation. There was a trend for successful nests from Oregon and British Columbia to occur in larger stands (mean 1,212 ac [491 ha]) than unsuccessful nests (mean 694 ac [281 ha]), although this was not statistically significant.

Bradley (2002) analyzed the success of nests found by telemetry in Desolation Sound, British Columbia, relative to their proximity to forest edges. Successful nesting was assumed if the radio-tagged adult visited the nest up to the midpoint in the chick-rearing period and was confirmed at some nests by tree climbing after the chick had fledged. Bradley (2002) conducted two analyses. One was from ground-based measures of distance from edge and nest success from 37 accessible nest sites, analyzed at 150 and 300 ft (46 and 91 m) distances from edge. At both distances, there were no significant differences in nest success at sites adjacent to or far from forest edges. Most nests were located adjacent to natural edges rather than artificial ones. Comparing nest success at natural and artificial edges was difficult, because only two nests were located directly adjacent to artificial edges (both were successful). Bradley's (2002) second analysis was a coarse-scale geographic information system (GIS) analysis using 98 nest sites, looking at edge type within 600 ft (182 m) of sites based on 1:250,000 landscape classification maps. In this analysis, the proportions of sites adjacent to edges versus interior were similar to those in the first ground-based sample. As in the first analysis, many nest sites were adjacent to natural edges, predominantly avalanche chutes, and most of these nesting attempts were successful (79 percent, n = 42). Nest success near artificial edges (61 percent, n = 23) and in forest interiors (48 percent, n = 33) was lower. Nests adjacent to natural edges had significantly higher success than those in the forest interior, but

Table 5-6—Summary of studies investigating the effects of habitat fragmentation, small patches, and forest edges on the success of marbled murrelet nesting

Study	Location	Type of study	Conclusions
Nelson and Hamer 1995	Rangewide	Review of early studies	Successful nests significantly farther from forest edges than failed nests. Corvid predation important.
Manley and Nelson 1999	Oregon and British Columbia—using some of same data as above	Review of early studies	38-percent success in nests <150 ft; 55 percent success in nests >150 ft. Predation responsible for at least 60 percent of failures.
Bradley 2002; see also Burger 2002	Desolation Sound, British Columbia	Nest success based on telemetry and post-fledging evidence	No negative effect of natural edges (e.g., avalanche chutes); insufficient data to test effects of clearcut edges.
Luginbuhl et al. 2001, Marzluff et al. 2000, Raphael et al. 2002b	Olympic Peninsula, Washington, and Oregon	Artificial nests with mimic eggs and chicks in natural nest locations	No consistent effects of forest fragmentation on nest survival. Proximity to human activity increased predation rates. Corvid predation important. Maturing forest bordering old-growth nesting habitat reduced predation risk.
Malt and Lank 2007	Southwestern British Columbia	Artificial nests with mimic eggs and chicks in natural nest locations	Predator visits significantly higher at edges (<150 ft) than in forest interior (>450 ft from edges), but no difference between "hard," "soft," and natural edges. Predatory corvids more likely at "hard" edges.
Malt and Lank 2009	Southwestern British Columbia	Artificial nests with mimic eggs and chicks in natural nest locations	Predator disturbance 2.5 times more likely at hard edges than in forest interior. Soft and natural edges not so. Corvid predation important. Maturing forest (20 to 40 years old) bordering old-growth nesting habitat reduced avian predation risk.
Hébert and Golightly 2006, 2007; Peery et al. 2004, 2006	Central and northern California	Telemetry and nest observations showing nest success in highly fragmented forests	84-percent nest failure; 67 to 81 percent of nests predated. Corvid predation important. Repeated use of same nest site associated with high predation.
Zharikov et al. 2006	Desolation sound, British Columbia	Nest success based on telemetry evidence only (new analysis using Bradley 2000 data)	Breeding success was greater in areas with recent clearcuts and lower in areas with much regrowth.

there were no significant differences between nests adjacent to artificial versus natural edges and artificial edges versus interior forest. In summary, Bradley's (2002) analysis did not support the hypothesis that nesting near forest edges was harmful to murrelets, but could not resolve whether natural or artificial edges produced differences in nest success. Bradley's (2002) study was limited because only 38 percent of the nests were accessible for ground-based measures and tree climbing, and proximity to edges for most nests was inferred from coarse-scale global positioning system (GPS) locations with ±100 m (328 ft) accuracy. The more detailed study by Malt and Lank (2007, 2009) in the same area and using some of the same nest data did find significant negative edge effects and differences between edge types (see below).

A later analysis by Zharikov et al. (2006) studied habitat selection and breeding success at nest sites located with telemetry in Desolation Sound (heavily logged; 121 nests) and Clayoquot Sound on the west coast of Vancouver Island (relatively intact; 36 nests). Comparing nest sites with randomly located points in these same areas, they found that murrelets used either old-growth fragments proportionately to their size frequency distribution (more intact landscape) or tended to nest in disproportionately smaller fragments (heavily logged landscape). Nests were closer to clearcut edges than expected, with mean distances to forest edges of 1.2 and 1.5 mi (1.9 and 2.4 km) at nest sites and randomly chosen points, respectively). Breeding success, as inferred from nest attendance patterns by radio-tagged parents, was modelled in Desolation Sound, where sample sizes were sufficient (Zharikov et al. 2006). They found that breeding success was greater in areas with recent clearcuts and lower in areas with much regrowth, implying that marbled murrelets can continue nesting in highly fragmented old-growth forests, successfully using patches of about 25 ac (10 ha) or greater. However, they cautioned that breeding success in fragmented areas may decrease as adjacent clearcuts overgrow, and that their findings imply that the same stands of old-growth forest may be equally attractive to marbled murrelets and logging companies, versus a murrelet preference for forest fragmented by logging (Zharikov et al. 2006). The finding by Zharikov et al. (2006) that murrelets can nest successfully in highly fragmented old-growth forests differs somewhat from results of other studies from British Columbia (Burger 2002); Burger and Page (2007) suggested that the spatial resolution and scale of the Zharikov et al. (2006) analyses were not sufficient to test edge effects (see Zharikov et al. 2007b for their response).

Because of the difficulties in locating and monitoring murrelet nests, several studies have resorted to using artificial nests with eggs or chicks mimicking those of the murrelet. Justification for this approach for studying murrelets is provided by Raphael et al. (2002b) and Malt and Lank (2007, 2009). "Predation" and disturbance by predators at artificial nests was based on removal, photographic or video evidence, movements detected by implanted motion sensors, or bite and peck marks made on wax coatings of eggs or chicks (Luginbuhl et al. 2001, Malt and Lank 2007, 2009). Artificial murrelet nests do not, of course, have an attendant parent, which might affect the rates of predation, although incubating adults have been attacked by ravens, and adults do leave eggs unattended for periods of several hours (Nelson and Hamer 1995). Murrelet chicks are brooded by adults for only a few days after hatching. The use of artificial nests to test predation effects has been criticized (e.g., Faaborg 2004), but their use has also been supported as allowing more rigorous and controlled quantitative experiments (Batáry and Báldi 2004). In the only study to compare the success of real and artificial marbled murrelet nests at various edge types, Malt and Lank (2007, 2009) found that artificial nests had significantly lower probabilities of disturbance (0.18 ± 0.05) than the probabilities of failure at real nests (0.35 ± 0.07), but the patterns of disturbance/failure were similar across edge types for real and artificial nests (reviewed below). If these results apply generally, then artificial nests seem unlikely to overestimate predation rates, and there is support for their application for studying edge effects in murrelets.

Intensive research on the likely impacts of forest structure and landscape contiguity on murrelet nest predation was undertaken by Marzluff and his team in the Olympic Peninsula, Washington, and in Oregon (Luginbuhl et al. 2001, Marzluff et al. 2000, Raphael et al. 2002b). Their experiments used painted plastic eggs and dark chicken chicks placed high in forest canopies to mimic those of murrelets. Video monitoring and marks on wax coatings identified predators, and field studies were supplemented with laboratory studies to test whether potential predators would attack eggs or chicks. Their field trials were focused on determining the effects of forest structure (simple or complex and of different ages), landscape contiguity (classified as fragmented when plots were more than 75 percent surrounded by clearcuts or contiguous when plots were more than 75 percent surrounded by mature forest), and proximity to human activities (near, less than 0.6 mi [1 km]), or far, more than 3.1 mi (5 km), from towns, farms, campgrounds, dumps, highways, etc.). Survival of simulated nests differed relatively little among the various forest cover types, and there were no consistent effects of forest fragmentation on nest survival but proximity to human activity increased predation rates. At locations far from human activity, predation rates were greater in continuous stands than in fragmented stands, but close to human activity, predation rates were similar in continuous and fragmented stands. The highest nest survival occurred in mature forest with simple structure, which were either contiguous and near human activity or fragmented and far from humans. Densities of corvids were lowest in contiguous, simple-structured maturing forests, regardless of proximity to humans, and corvid numbers differed little among the other forest cover categories. It is difficult to infer generalizations from these results, apart from negative effects of proximity to human activities, but Marzluff et al. (2000) suggested that old-growth stands used by murrelets for nesting might be best buffered by surrounding the stands with maturing, simple-structured forests in which there were relatively few predators.

In the same study, Luginbuhl et al. (2001) reported a strong negative correlation between survival of simulated murrelet eggs and corvid abundance at the landscape level (2 to 20 mi^2 [5 to 52 km^2] scale). Corvid abundance explained 69 percent of the variance in predation of simulated murrelet eggs. This trend was not evident at smaller plot-level scales (60 to 120 ac [24 to 49 ha]). The cause of this scale-sensitive relationship was likely due to the large home range of some of the corvid species (ravens and crows). For monitoring and management purposes, this result implies that such negative correlations might not be evident unless large spatial scales are considered. Artificial nests in areas with high use by Steller's jays lasted only half as long as those in low-use areas (Vigallon and Marzluff 2005).

Malt and Lank (2007, 2009) used artificial nests with painted eggs and stuffed quail chicks to study predation rates likely to apply to murrelets relative to edges in four sites in British Columbia. Avian predators caused more than half of the disturbances, with squirrels and mice also frequent. Artificial eggs were disturbed more frequently than nestling mimics, and birds and squirrels disturbed eggs more than nestlings, but the reverse was true for mice. In their first study (Malt and Lank 2007), disturbances of nest contents by all predators was significantly higher at edges (less than 150 ft [46 m]) than in the forest interior (more than 450 ft [137 m] from edges), but there was no difference between "hard," "soft," and natural edges. In both studies, predation of eggs by birds (mainly corvids) was always higher at hard edges than in interior forest, but soft or natural edges did not show this effect. Predation on nest contents by squirrels and mice was more variable regionally and with forest type, but generally predation by mice was not strongly affected by edges (although higher at natural edges than in adjacent interiors). They found no edge effects from squirrel predation in their first study (Malt and Lank 2007), but in their second study squirrel predation was higher at all edge types than in adjacent interior forest (Malt and Lank 2009).

At the landscape scale, Malt and Lank (2009) found that avian predation risk was negatively affected by the percentage of regenerating forest 20 to 40 years old; i.e., the risk of egg predation decreased by more than half if the bordering regenerating forest increased from 1 to 40 percent. This matches the conclusions by Marzluff et al. (2000) on the buffering effects of regenerating younger forest. Malt and Lank (2007) also reported higher predation in landscapes with a higher proportion of old-growth forests, which might indicate that recent clearcuts and regenerating forests supported fewer predators overall.

Some important trends emerge from the work of Malt and Lank (2007, 2009). Predation risk from avian predators was considerably higher than from mammals, and the birds were more likely to target eggs than nestlings. This risk from avian predators was particularly high at hard edges, but much less likely at soft or natural edges, and the landscape-level analysis indicates that this is likely due to reduced predation risk as the regenerating matrix changes from clearcut to young (20- to 40-year-old) forest. They also found strong edge effects among squirrels, which is contrary to the general belief that squirrels are less attracted to edges than birds, such as corvids (Marzluff and Restani 1999).

The reduction and fragmentation of old-growth forests can also lead to the undesirable situation in which murrelets and some of their predators (especially old-growth-dependent species such as goshawks) are restricted to using the same small patches. This could lead to greater risk of predation. If adult murrelets are put at risk in this way, it would have serious consequences for populations.

Nesting murrelets and their eggs and chicks are at risk to a formidable array of potential predators, and the murrelet's cryptic and widely spaced nest sites, secretive and crepuscular visits to nests, and camouflaged breeding plumage are all obvious adaptations to reducing predation risk. Although it is difficult to estimate the predation impacts of the complete suite of predators (birds and mammals) in any area, it is clear that corvids, especially Steller's jays and common ravens, are the most common nest predators across the murrelet's range (McShane et al. 2004, Nelson and Hamer 1995, Piatt et al. 2007). Both of these species and, in some situations, other predators like squirrels (Malt and Lank 2007, 2009), exhibit strong affinities with forest edges (Marzluff et al. 2000). Murrelets nesting at edges, and especially hard edges bordering open areas like clearcuts, appear to be at greater risk of predation than in the forest interior. Given that nest predation appears to be a dominant demographic driver for the murrelet (McShane et al. 2004; Nelson 1997; Peery et al. 2004, 2006a; Piatt et al. 2007), any forest alteration that increases predation risk is likely to have a negative and perhaps serious impact on local murrelet populations. Reducing predator risks by minimizing edge habitats and controlling corvid access to garbage and human food (e.g., at campsites) is also likely to benefit murrelets in modified landscapes.

The situations in northern California, documented by Hébert and Golightly (2006, 2007) and in central California by Peery et al. (2004, 2006b), illustrate how massive nesting habitat loss and limited nesting options for murrelets lead to a classic habitat trap situation (Battin 2004). Murrelets nesting in those regions are concentrated in the relatively small patches of suitable redwood forests remaining, and reuse of the same trees and nest sites is higher than what is recorded elsewhere (Burger et al. 2009; Hébert and Golightly 2006, 2007). These trees and nest sites are repeatedly visited by corvids (Steller's jays and common ravens), and consequently nesting success is extremely low in conservation zone 6 at the southern end of the murrelet's breeding range, where 84 percent of nests fail and predation rates at nests are 67 to 81 percent (Peery et al. 2004). Along with periodic food shortages linked to oceanic variability, nest predation is considered to limit this population, which appears to be sustained by immigration (Peery et al. 2004, 2006a, 2007). Reducing corvid populations (Peery and Henry 2010) and aversion conditioning to reduce nest predation by Steller's jays (Gabriel and Golightly 2014) are potential management strategies to help maintain this marginal population of murrelets. This extreme situation might not be typical of other less-modified parts of the murrelet's range, but is likely similar in northwest Oregon, southwest Washington, and northern California, and on Bureau of Land Management lands in Oregon where the landscape is highly fragmented. These situations indicate the risks of excessive habitat reduction and fragmentation.

In summary, this review shows that many factors affect the risks to murrelets when they nest near forest edges or in small forest patches, including the type of edge, the type of habitat bordering the edge, the suite of predators likely, and proximity to human activity (table 5-6). In most situations, particularly where ravens and jays are common, nesting near (<150 ft [46 m]) "hard" edges (i.e., the bordering regenerating forest is less than 20 to 40 years old) will increase predation risk.

Marine habitat—

The NWFP is tightly linked to the status and trends of murrelets because its lands provide the majority of suitable nesting habitat within the species' listed range in Washington, Oregon, and California. Recent analyses indicate that nesting habitat conditions best explain the abundance and trends of murrelets at sea off the NWFP area during the breeding season (Raphael et al. 2015, 2016b). A breeding-season pattern of murrelets tending to occur offshore of nesting habitat is consistent with nesting murrelets behaving as central-place foragers, subject to energetic constraints that limit them to foraging within some radius of their nest location—the "central place" (Raphael et al. 2015). Murrelets depend entirely on marine prey, and because of this, prey conditions such as abundance and quality, and the underlying factors affecting prey conditions, are important to the future of the murrelet in the Plan area and elsewhere. Thus, the juxtaposition of productive foraging habitat offshore of nesting habitat may be important to murrelet conservation. Notably, reviews of murrelet biology (McShane et al. 2004, Piatt et al. 2007) indicate that the distribution of foraging murrelets is strongly influenced by patterns of prey availability (and perhaps juxtaposition to nesting habitat), while other studies found that prey quality or availability influence breeding success (Becker et al. 2007, Gutowsky et al. 2009, Norris et al. 2007).

Below, we summarize those recent analyses that evaluated the relative contributions of marine conditions and nesting habitat conditions to murrelet status and trend in the Plan area, and review the larger body of scientific information on the relationships between marine habitat conditions and murrelet biology throughout the species' entire range.

To understand the murrelet's marine habitat, it is helpful to introduce some key features of that habitat. First, most of the marine waters off the NWFP area are within the California Current system, the southward-moving surface current of colder water from the north Pacific. A key characteristic of the system is wind-driven upwelling of cooler and typically nutrient-rich waters to the surface in nearshore areas, particularly in spring and summer. This upwelling of nutrients results in increased productivity (Batchelder et al. 2002), and may be key to maintaining cold, productive marine conditions favorable to murrelets south of Washington state, in areas that would have warmer sea temperatures in the absence of the current system and upwelling (McShane et al. 2004).

The Puget Sound/Salish Sea region differs from elsewhere in the Plan area; it is not dominated by the California Current, and it has a more complex nearshore geography shaped by glaciation and with many islands, like many areas to the north, which creates local currents and tidal patterns that concentrate prey.

***Marbled murrelet prey*—**Marbled murrelets prey on a wide range of marine fish and invertebrates (Burkett 1995, Nelson 1997). Murrelets appear to have a flexible foraging strategy, exploiting the prey species and foraging locations that maximize energy gain (Piatt et al. 2007). For example, murrelets selected less abundant, higher value Pacific herring (*Clupea pallasii*) at times over other, more abundant species (Ostrand et al. 2004), and sometimes foraged in deeper waters than normal, where local conditions created prey concentrations near breeding areas (Kuletz 2005).

Species composition of available prey changes across the murrelet's range, perhaps most notably between the California Current system and the Alaska Current system, which dominates the species' range north of the NWFP area. Common murrelet prey species include sand lance (*Ammodytes hexapterus*) and smelt (family Osmeridae), which are taken by murrelets in many areas, as are small herring and krill (*Thysanoessa* spp. and *Euphausia* spp.), where available. As one moves north, and particularly north of the California Current area, sand lance, capelin (*Mallotus villosus*), and small Pacific herring are frequent murrelet prey (Bishop et al. 2014, McShane et al. 2004, Piatt et al. 2007); all three of these species are of moderate to high quality in terms of energy content (Anthony et al. 2000). Of these, capelin do not occur from the Olympic Peninsula southward, and sand lances become scarce in some areas to the south of the peninsula. Within the California Current, northern anchovy (*Engraulis mordax*) and, in spring, juvenile rockfish (*Sebastes* spp.) are dominant small schooling fish in nearshore waters (McShane et al. 2004), and are taken by murrelets (Burkett 1995). Although fish tend to dominate the murrelet diet and exclusively comprise prey brought to the nest, invertebrates, particularly krill, are taken at times by adults throughout the murrelet's range.

***Marine proxies for prey abundance in the NWFP area*—**As part of the 20-year monitoring report and related work, the NWFP effectiveness monitoring program analyzed the relative influences of marine and terrestrial factors on murrelet distribution and population trends during the first two decades of the NWFP (Raphael et al. 2015, 2016b). Although the murrelet diet has been studied to the north of the Plan area, particularly in Alaska (summarized in McShane et al. 2004 and Piatt et al. 2007), few studies have been conducted on the murrelet diet south of Canada, and monitoring data for murrelet prey species from waters off NWFP lands are equally sparse. For these reasons, Raphael et al. (2015, 2016b) used physical and biological attributes of marine habitat as proxies for local prey abundance in their analyses. The attributes that the authors measured included chlorophyll "a" concentration in ocean surface waters and sea surface temperature, which have been used in comparable analyses by others (e.g., Ainley and Hyrenbach 2010, Hazen et al. 2012), and are available at relatively fine temporal and spatial scales. The idea is that cooler water is rich in nutrients. This in turn leads to a more robust food chain, ultimately leading to a more robust supply of small fishes and invertebrates that murrelet prey upon. Cooler waters are enriched with nutrients compared with warmer waters, and are frequently associated with upwelling. Chlorophyll "a" concentration has for decades been a proxy for phytoplankton abundance and primary productivity, and performs well in this role (Huot et al. 2007). In the northeast Pacific (Ware and Thomson 2005) and California Current (Reese and Brodeur 2006), chlorophyll "a" concentration was positively associated with fish abundance, as was phytoplankton abundance in the North Sea (Frederiksen et al. 2006). In the California Current, chlorophyll "a" peak abundance was a strong predictor of seabird abundance and hotspots of seabird density (Suryan et al. 2012). For these reasons, Raphael et al. (2015, 2016b) hypothesized that murrelet prey abundance would be positively associated with primary productivity.

Marbled murrelet prey availability is likely to be affected by broader Pacific Ocean conditions, including the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997) and the El Niño Southern Oscillation (ENSO) (Trenberth 1997), which have widespread effects on marine productivity and food webs, as well as on seabird populations, including other diving seabirds in the California Current system (Ainley and Hyrenbach 2010). Therefore, the 20-year NWFP analyses also included factors to account for variability in PDO and ENSO conditions (Raphael et al. 2016b). The ENSO is a pattern of periodic changes (events), typically lasting about 9 to 18 months, that produce (1) El Niño events with increased sea surface temperatures and reduced coastal upwelling, and (2) La Niña events that result in colder, more nutrient-rich waters than usual (Mestas-Nunez and Miller 2006, Schwing et al. 2002). The PDO represents long-term (20 to 30 years) climate variability in the north Pacific Ocean, in which there are observed warm and cool phases, or "regime shifts" with corresponding patterns of weaker or strong upwelling (Mantua et al. 1997). Later (see "Climate Change Considerations" below), we discuss potential effects of climate change on murrelet prey and these proxies.

Associations with marine habitat and prey—Although prey and foraging habitat conditions differ across the murrelet's wide range, murrelets forage and rest mostly in shallow nearshore waters associated with the continental shelf (Nelson 1997). Murrelets often use sheltered waters when available (Nelson 1997), but most of the coast in the Plan area (except for the Puget Sound area) lacks the complex structure and sheltered areas found farther north in the glaciated fjords and abundant islands of Alaska and British Columbia. In the Plan area, data from the at-sea work of the NWFP effectiveness monitoring program shows that most murrelet foraging during the breeding season occurs in water depths of 80 ft (24 m) or less, except for the San Juan Islands and northern Puget Sound, where murrelets used waters up to 130 ft (40 m) depth (Raphael et al. 2016b).

Analyses for the 20-year NWFP murrelet report examined variation in murrelet abundance in relation to dominant shoreline substrate within the Plan area, and found that murrelet abundance was greater offshore of fine- to medium-grained sand beaches and was also greater offshore of estuaries and marshes, compared to other substrates (Raphael et al. 2016b). In an earlier study of murrelet habitat use off southern Oregon, murrelets were most abundant near ocean bays, river mouths, sandy shores, and submarine canyons (Meyer and Miller 2002). Similarly, murrelet densities off British Columbia were highest over sandy substrate, near estuaries, and where waters are coolest (Burger 2002,, Piatt et al. 2007, Ronconi 2008, Yen et al. 2004). In a study at the southern end of the murrelet's range near Santa Cruz, California, Becker and Beissinger (2006) found that foraging murrelets appeared to prefer cooler waters associated with areas of recent upwelling.

In their review of murrelet ecology, Piatt et al. (2007) concluded that physical and biological oceanographic processes that concentrate prey (such as upwellings and rip currents) have an important influence on where murrelets forage. Although that conclusion is largely based on work in Alaska and British Columbia (e.g., Burger 2002, Day and Nigro 2000, Kuletz 2005), it is supported by work in Washington, Oregon, and California (Ainley et al. 1995, Nelson 1997, Strong et al. 1995). This suggests that, at the finer scale, across their range, murrelets select foraging areas based on similar topographic and oceanic factors associated with higher prey densities in shallower waters. This pattern is consistent with the often strong positive relationship between forage fish abundance and the abundance of fish-eating birds (e.g., Durant et al. 2009, Furness and Tasker 2000).

Changes in foraging habitat conditions—There is some information from analyses of stable isotopes in murrelet tissues indicating long-term declines in murrelet diet quality in portions of its range in central California (Becker and Beissinger 2006), the Salish Sea, including northern Washington (Gutowsky et al. 2009), and British Columbia (Norris et al. 2007). At least one of these studies suggested that murrelet foraging success along the Pacific Coast is sensitive to climate variability, and that cooler ocean waters and resulting prey conditions are associated with greater reproductive success (Becker et al. 2007). Further, though murrelets have flexible foraging and life history strategies that presumably evolved in an environment of varying prey conditions, there is evidence that declines in murrelet diet quality may have contributed to reduced murrelet reproductive success in the Salish Sea (Gutowsky et al. 2009), and that foraging flexibility in murrelets (Ronconi and Burger 2009) and other alcids (Schrimpf et al. 2012) may not be sufficient to avoid low reproductive success when environmental conditions are extremely poor. Adult survival in murrelets appears less vulnerable to poor forage conditions than does reproductive success (Beissinger and Peery 2007, Peery et al. 2006a, Ronconi and Burger 2008), and Ronconi and Burger (2008) proposed that murrelets likely have a life history strategy in which adults do not initiate nesting, or abandon nesting attempts, to maximize their own survival when available forage is inadequate. Piatt et al. (2007) concluded that climate-related changes in marine ecosystems, in addition to human activities (logging, gill net bycatch, oil pollution), were the likely reasons for the wide-scale declines in murrelet populations in British Columbia and Alaska.

Environmental conditions, particularly El Niño events, have been shown to markedly reduce prey availability for some seabirds in California, leading to poor reproductive success (Ainley et al. 1995). Although El Niño events appear to reduce overall seabird prey availability, their effect on murrelets are not well known. Inner coastal waters in the Puget Sound and the Strait of Juan de Fuca, as well as estuarine areas along the outer coast, appear less influenced by El Niño conditions because of mixing and nutrients from sources other than outer coastal waters (USFWS 1997). In addition to ENSO variation, it is known that fish populations and zooplankton in the California Current generally do better during “cold” than in “warm” phases of the PDO, while in the more northerly Alaska Current, some fish populations such as salmon behave oppositely (Hallowed et al. 2001).

The 20-year NWFP analysis found only one forage-fish dataset from the Plan area of interest, and which spanned the period of that analysis (Raphael et al. 2016b). Those data provided abundance of forage fish from two transects located just north and south of the Columbia River. For this limited area, the authors found some evidence in the year-to-year variation of a positive relationship between forage fish and murrelet abundance, and concluded that direct measures of forage-fish abundance as predictors of murrelet abundance need additional investigation (Raphael et al. 2016b).

Climate Change Considerations

The Intergovernmental Panel on Climate Change (IPCC) is a scientific body that was set up in 1988 by the World Meteorological Organization and United Nations Environment Program to inform policymakers about the causes of climate change, its potential environmental and socioeconomic consequences, and the adaptation and mitigation options to respond to it. In 2014, the IPCC published its Fifth Assessment Report, which is widely considered the most comprehensive compendium of information on actual and projected global climate change currently available. Although the extent of warming likely to occur is not known with certainty at this time, the IPCC has concluded that warming of the climate system is unequivocal: that the atmosphere and ocean have warmed, sea level has risen, and continued greenhouse gas emissions will cause further warming (IPCC 2014). Ocean warming accounts for more than 90 percent of the energy accumulated and stored in the climate system between 1971 and 2010 (IPCC 2014). Although the report does not focus on changes at the scale of the NWFP, it did find with high confidence new evidence for decreasing spring snowpack in western North America.

Climate change and terrestrial nesting habitat—
Although murrelets spend most of their time in the marine environment, murrelets require suitable forest cover for nesting. The U.S. Fish and Wildlife Service reviewed potential threats to murrelet nesting habitat in its last status review (USFWS 2009). The agency concluded that, based on climate model projections, the future conditions of forests where murrelets nest will be largely unfavorable for maintaining current forest structure and composition. Projections suggest that increases in annual temperature changes within the range of the murrelet will be greatest in the summer and lowest in the spring, but predicted that temperature increases near the coast will be generally lower than in the rest of the Plan area (Dalton et al 2013). Already in the Pacific Northwest, tree mortality rates in unmanaged old forests have increased in recent decades at a rate equivalent to doubling over 17 years (van Mantgem et al. 2009), a change the authors suggested was likely due, at least in part, to documented regional warming and drought stress associated with climate change. With respect to drought stress, Johnstone and Dawson (2010) found evidence of a 33 percent reduction in fog frequency over the past century in the coast redwood forest zone of northern California, which includes most of the nesting habitat in conservation zone 5 and in the California portion of conservation zone 4. Based on tree physiological data, they suggested that redwood and other western coastal forest ecosystems may experience increasing drought stress as a result of reduced summer fog and greater evaporative demand.

During the next 20 to 40 years, climate projections for the Pacific Northwest indicate likely decreases in Douglas-fir growth from drier summers (Littell et al 2010). Heat extremes and heavy precipitation events are likely to become more frequent (Loehman and Anderson 2009). With these changes, the potential exists for increased fire frequency and severity, even in the coastal forests where murrelets nest (Millar et al. 2006). In North America broadly (Dale et al. 2001) and the Pacific Northwest specifically (Kliejunas et al. 2009; Littell et al. 2009; Mote et al. 2003, 2010), climate changes may also alter forest ecosystems via the frequency, intensity, duration, and timing of other disturbance factors such as drought, introduced species, insect and pathogen outbreaks, windstorms, ice storms, landslides, and flooding. Evidence for an increased role of fire within the range of the murrelet is mixed, with some models projecting increases and others projecting decreases (see chapter 2, "Climate," and chapter 3, "Vegetation Change"), but the historical occurrence of large, high-severity fires suggests the potential for losses in nesting habitat if fires do occur (Agee 1993). Overall, the evidence is substantial that climate change will result in changes to forest habitats where murrelets nest. The magnitude of those changes is less known, as is how nesting murrelets and murrelet populations will respond to forest changes. However, to the extent that changes such as increased tree mortality, decrease in canopy epiphytes, and increased severity and frequency of fires reduce the number of potential nest trees, impacts to murrelets appear likely to be negative.

Climate change and marine habitat—
In addition to influencing the quality and abundance of nesting habitat, as discussed above climate change is likely to result in changes to the murrelet's marine environment, with effects on murrelet food resources the most likely mechanism. Given the large body of climate change literature, we focus our review here on such potential effects on prey resources.

The U.S. Fish and Wildlife Service reviewed the potential effects of climate change on murrelets south of Canada, and concluded that—although predicting climate change effects on marine resources is complex and has many uncertainties—taken as a whole, the evidence from models and other sources suggested that few changes are likely to benefit murrelets, with many more having the potential for neutral or adverse effects (USFWS 2009). The same review found it most likely that the murrelet prey base will be adversely affected to some extent by climate change, and noted that although seabirds generally have life-history strategies adapted to variable marine environments, ongoing and future climate change could present changes of a rapidity and scope outside the adaptive range of murrelets (USFWS 2009).

Marine changes already observed may be attributable to climate change. El Niño events have become more frequent, persistent, and intense during the last decades of the 20th century (Snyder et al. 2003). There is general agreement that sea surface temperatures will increase as a result of climate change, with evidence that they have already increased in murrelet marine habitat off the NWFP area by 0.5 to 1.0 °C (about 1 to 2 °F) over the last half century, both in the California Current system (Di Lorenzo et al. 2005) and in the Strait of Juan de Fuca (Rucklehaus and McClure 2007). In the murrelet's nearshore environment, upwelling of cold waters may moderate some level of sea-surface-temperature changes, but differences in the timing, intensity, and duration of upwelling can affect productivity, resulting in considerable uncertainty regarding the ultimate effects of marine changes on murrelet foraging conditions. Climate models show inconsistent projections for the future of coastal upwelling in the Pacific Northwest (Melillo et al. 2014). Illustrating the complexities of making such projections, Sydeman and others (2014) conducted a meta-analysis of the literature on wind intensification in coastal upwelling marine systems over the prior six decades. They found support for wind intensification in the California Current system and noted that this could increase nutrient input and benefit marine populations if primary production is nutrient limited. However, they emphasized the complexity of forecasting the consequences of wind intensification in coastal ecosystems because the ecological effects are likely sensitive to diverse factors including phenology of upwelling-favorable winds, patterns of nutrient transport offshore, differing responses of food web species, and potential for increased stratification resulting from increased water temperatures (Sydeman et al. 2014).

Climate change is anticipated to result in sea-level rise and a decrease in the pH of marine waters, with unknown effects in both the California Current system and Puget Sound. Increasing acidification of marine waters caused by increased absorption of carbon dioxide from the atmosphere may have significant impacts on marine food webs. This is because acidification reduces the availability of calcium ions for the formation of calcium carbonate, an essential component of the skeletons of marine plankton, shellfish, and other organisms (Doney et al. 2012, Feely et al. 2008). In the Pacific Northwest, which includes Oregon and Washington, projected marine changes include increasing but variable acidity, more increases in surface water temperature, and possible changes in storminess (Melillo et al. 2014). In Puget Sound, changes in the timing and amount of freshwater inflow may produce fresher waters during winter and saltier waters during summer, resulting in stronger stratification in winter and weaker stratification in the summer (Rucklehaus and McClure 2007).

Although physical changes to the marine environment appear likely, much remains to be learned about the magnitude, geographic extent, and temporal and spatial patterns of change, and their effects on murrelets (USFWS 2009). However, we do know that climate variability can strongly influence the foraging and reproductive success of seabirds, including the murrelet (Becker et al. 2007, Grémillet and Boulinier 2009, Norris et al. 2007). Shifts in the intensity of upwelling influence nutrient availability and primary productivity in coastal waters, with cascading effects at higher trophic levels (Thayer and Sydeman 2007). For example, El Niño events have been associated with poor seabird survival and recruitment in the eastern Pacific (Bertram et al. 2005, Hodder and Graybill 1985). Some species respond more strongly to either the ENSO or PDO phases, but not both (Black et al. 2011, Sydeman et al. 2009), and the local effect of regional patterns such as the ENSO and PDO is modified by undersea topography, trophic interactions, bird movements to track prey, and food web impacts from commercial fisheries harvest (Doney et al. 2012). Although many seabirds have flexible foraging strategies, chronic food scarcity can compromise long-term breeding success (Cury et al. 2011) and reduce adult survival and fecundity (Kitaysky et al. 2010).

With respect to foraging strategies, Lorenz et al. (2017) reported on marbled murrelet movements during the breeding season, based on the radio-tracking of 157 birds between 2004 and 2008 in northwestern Washington. The authors did not find oceanographic conditions to substantively explain variation in movements of foraging murrelets. They did find low breeding propensity, large marine ranges, and long nest-sea commutes compared to studies elsewhere in the murrelet's range, and hypothesized that this may indicate that marine habitat in their study area was lower quality compared to elsewhere in the species' range. They also found, unexpectedly, that a recent widespread and strong delay of the onset of spring upwelling in the California Current in 2005 did not appear to substantially affect murrelet movements or breeding propensity. This finding differs from that of Ronconi and Burger (2008), who linked reduced murrelet breeding productivity in southwestern British Columbia to the 2005 upwelling delay.

If recent warm-water events are an indicator of future effects of increased sea-surface temperatures, the murrelet prey base could be negatively affected. Studies of other diving seabirds such as Cassin's auklets (Sydeman et al. 2006), historical versus recent murrelet diet (Becker and Beissinger 2006), and recent annual variations in murrelet reproductive success (Becker et al. 2007) suggest that warmer coastal waters tend to adversely affect prey quality and result in lowered reproduction.

Research Needs, Uncertainties, Information Gaps, and Limitations

The challenges of accurately sampling such a mobile and patchily distributed species result in fairly large uncertainty around each year's density and population estimates, as seen in the confidence intervals. The NWFP population monitoring data provide 15 years from which to assess population trends and, based on the observed sampling error, power analysis indicates that 15 or more years of population estimates are required to detect an annual rate of decline of 2 percent (Falxa et al. 2016). Even with these constraints, the population monitoring data for 2000 through 2015 indicate a marked decline in Washington, no evidence of a trend in Oregon, and an increasing trend in California. Additional years of population monitoring will increase the power to detect ongoing trends, such as those of 2 percent or less per year. Conversely, population trajectories can change over longer monitoring periods, resulting in nonlinear trends, which adds temporal variability and complexity in describing trends.

A major source of uncertainty is whether the murrelet population is closed or open. That is, existing population models (such as McShane et al. 2004) assume there is little or no recruitment of adults or juveniles from outside the study population, and little or no emigration out of the study population. For example, the local population may be declining but is being supplemented by immigrants, perhaps from Alaska or British Columbia, where murrelets are more numerous. Recruitment of birds from outside the local range has been proposed as the most likely explanation for the seemingly stable population estimates in central California (Peery et al. 2006a), despite demographic models that predict a decline (Peery 2004). The open population hypothesis, at least for their range from southern Alaska through northern California, is supported by genetic analyses (Piatt et al. 2007), and recent studies showing long-distance movements of murrelets tracked by satellite (e.g., Bertram et al. 2015b). However, it is not known if movements of murrelets are sufficient to affect population estimates and trends within the NWFP area.

Future population trends are difficult to predict because of uncertainties in the timing and extent of risk factors. Catastrophic loss of nesting habitat from uncharacteristically severe wildfire is an ever-present risk. Among factors other than habitat loss, murrelets at sea are subject to risk from large oil spills at sea (USFWS 1997); oil spills killed an estimated 872 to 2,024 murrelets between 1977 and 2008 in California, Oregon, and Washington (USFWS 2009). A recent review concluded that spills continue to be a threat and can cause severe localized impacts owing to direct mortality from oiling, as well as reductions in reproductive success through changes in prey base, marine habitat, and disturbance (USFWS 2009). Gill net mortality was cited as a factor for listing the murrelet in 1992. Since then, this risk has been substantially reduced in the NWFP area, with no mortality in California and Oregon because of gill net bans, and reduced mortality in Washington as a result of measures implemented to reduce seabird mortality (McShane et al. 2004, USFWS 2009). Gill net mortality remains a threat to the north in British Columbia and Alaska, however, and could be a risk to the NWFP murrelet population to the extent that murrelets move between waters off the Plan area and marine waters to the north. Future energy development, both at sea and on land, could also pose a local threat to murrelets, such as potential collisions with wind turbines (USFWS 2009).

Changes in prey base present risks as well. As discussed earlier, studies have found evidence that murrelet reproductive success is influenced by prey availability, and future prey resources can be affected by fishing as well as changes in ocean conditions, including those linked to climate change. In some other seabird species (e.g., Montevecchi and Myers 1997), changes in ocean currents can have profound effects on forage fish, leading to starvation in addition to breeding inhibition. For murrelets, one study found that adult survival appears less vulnerable to prey shortages (Ronconi and Burger 2008). To date, disease has not been found to be a significant threat to murrelets (Piatt et al. 2007, USFWS 2009), but pathogens new to the region could cause direct mortality to nesting birds, and could also have indirect effects (USFWS 2009). For example, the West Nile virus is documented to kill jays, crows, and ravens, and if mortality of these species resulted in appreciable reductions in their densities, this might increase nest success of murrelets by reducing nest depredation.

Raphael et al. (2016a) describe sources of uncertainty in estimating the amount and distribution of nesting habitat of the murrelet. But one additional source warrants further mention. Because murrelet nesting behavior is so cryptic, biologists have found very few actual nests of the species. To supplement actual nesting observations, biologists rely on locations of "occupied behaviors" to infer nesting activity. Occupied behaviors are observations of murrelets flying into the canopy, circling very close above the canopy, or landing in trees. These behaviors are typically associated with nesting, but some sites where occupied behaviors are observed may not be true nest sites. To the extent that false positives may be included in the murrelet database used to build models, these models may be less accurate than if all locations were based on verified nests (Plissner et al. 2015). A more reliable modeling solution would be to conduct intensive research to identify more known nest sites across a broad sampling of regions within the NWFP area, then build models exclusively from training sites that represent actual murrelet nests. Such intensive surveys would also help our understanding of spacing and density of nesting activity in relation to forest stand characteristics.

Some uncertainty also exists in the distance that murrelets fly inland to nest and how that varies within the Plan area. The Forest Ecosystem Management Assessment Team designated two inland zones within the area in which murrelets nest: Inland zone 1 formed the area closer to the marine environment, and inland zone 2 was further inland, extending to the eastern boundary of the species' nesting range (see fig. 5-4). Nesting was assumed to occur mostly in zone 1. Recent survey-based studies in some areas have led to local contractions of zone 2, especially in northern California and southern Oregon (Alegria et al. 2002, Hunter et al. 1998, Schmidt et al. 2000). Agencies in those areas have redefined the eastern boundary of the area in which surveys for murrelets are required prior to timber harvest, bringing it farther to the west to match study results. This revised boundary has not been formally implemented in the NWFP agency maps; to date this revision applies only to survey requirements for management units where the studies were conducted. This strategy adds uncertainty in the calculation of nesting amounts of nesting habitat to the extent that acres classified as nesting habitat may actually fall outside the species' true breeding range. This uncertainty is reduced in the most recent analysis by the NWFP monitoring program, which did not model or estimate suitable murrelet nesting habitat in inland zone 2 in California or Oregon; this is because of the lack of inland zone nest sites in those states with which to train the nest habitat models (Raphael et al. 2016a).

We found no studies documenting the response of murrelets to silvicultural activities designed to accelerate expression of mature forest conditions, and this remains an area in which much further research is needed. Foresters have conducted studies using experimental thinning prescriptions, but none of these has incorporated responses of murrelets to these treatments.

Perhaps the most important area of uncertainty is the relationship between murrelet population size and trend and the influences of either amount and trend of nesting habitat versus variation and trends in ocean conditions that affect foraging habitat. The studies that we summarize point toward nesting habitat as the primary driver, but all these studies concede that relationships are correlational. Cause-effect relationships have not been established, so further work will be needed to confirm whether these correlations reflect true underlying causes.

Conclusions and Management Considerations

Are NWFP Assumptions Still Valid?

Nesting habitat status and trend—
The NWFP has played a pivotal role in the fate of murrelet nesting habitat on federal lands. The Plan has been highly successful in conserving existing murrelet nesting habitat, and little nesting habitat has been lost to timber harvest on federal lands. Some loss of nesting habitat, especially in federal reserves, was caused by fire. Loss of murrelet nesting habitat to catastrophic events will always be a risk, and such losses were expected. The NWFP has less control over the risk of such losses, except to the extent that active management in fire-prone areas might reduce the risk of fire in younger forests in proximity to murrelet nesting habitat, and by reducing vegetation that could transmit fire to the canopy of murrelet nesting trees, such as in forests with scattered nest trees within younger forest. One caution should be recognized: managing forest cover to reduce fire risk could also lead to better habitat for corvids (nest predators); silvicultural practices near suitable murrelet nesting habitat may need to be fine-tuned to ensure they do not inadvertently impair nesting success of murrelets by increasing the rate of nest depredation. In addition to active fire management, another area for potential reduction of nesting habitat loss on federal lands is management to reduce the risk of windthrow associated with the creation of hard edges. In this case, the greatest potential benefit to murrelets would be in (1) creating and maintaining forested buffers adjacent to existing known and suitable murrelet nesting habitat, and (2) developing nesting habitat within reserves plus in adjacent buffers.

The fate of nesting habitat on nonfederal lands is beyond the scope of the NWFP; 67 percent of habitat-capable forest is in nonfederal ownership, as is 41 percent of suitable murrelet nesting habitat. The rate of loss of suitable nesting habitat on nonfederal lands (1.5 percent per year) has been far more rapid than on federal lands (0.1 percent per year).

The requirement for preproject surveys on federal land was assumed to prevent the loss of any occupied sites from timber harvest. We are not able to test this assumption because we have no way to assess whether sites on federal land were classified as unoccupied when they might actually have been occupied. Occupied behaviors are not observed at every visit to a site; a finite likelihood exists of failing to detect occupied behaviors even if the site is occupied. The protocol used to determine site occupancy (Evans Mack et al. 2003) sets the numbers of visits required to have a high likelihood (set at 0.95) of observing occupied behavior at an occupied site. Under this protocol, a 5-percent chance of failing to detect occupied behavior exists, so a small number of sites might be mistakenly classified as unoccupied and released for timber harvest. The Pacific Seabird Group (a society of professional seabird researchers and managers dedicated to the study and conservation of seabirds) is considering a revision of the current survey protocol (Evans Mack et al. 2003), which would use the best available science to ensure that the 5 percent criterion is met by the protocol. We can say that sites classified as occupied were, in fact, set aside and managed as LSR3 reserves. There apparently have been some differences among NWFP management units in applying the NWFP standards and guidelines to occupied sites, with some reserves including all forest within a 0.5-mi (0.8 km) radius (which provides a larger block and more protection), and others including only contiguous forest within the radius that is existing suitable or recruitment murrelet nesting habitat (USDI BLM 2016).

Population status and trends—
Murrelet populations are affected by a variety of factors, only some of which are under the NWFP's direct influence. The Plan most directly affects populations through its provisions for conservation and restoration of nesting habitat, but even then its influence extends only to federal lands. Although NWFP forest management may have minor or local effects on marine habitats, such as through altered input of sediment and coarse wood, overall the Plan has little to no influence on marine conditions affecting murrelet populations (including marine food sources) or on sources of mortality at sea, such as oil spills and gillnetting. This makes it more difficult to relate changes in murrelet populations to land management under the NWFP. With the NWFP conserving nesting habitat as expected, murrelet populations could still fall because of adverse marine

conditions or because of nesting habitat loss on nonfederal lands. Despite this uncertainty, circumstantial evidence suggests that inland nesting habitat conditions are the major driver setting murrelet population size at this time. This point is illustrated in Raphael et al. (2016b), in which the authors found a positive correlation with the total amount of nesting habitat and size of adjacent murrelet population for segments of the murrelet range. In addition, Raphael et al. (2015, 2016b) constructed a model to assess relative contribution of marine and terrestrial habitat attributes toward abundance and trend of murrelets throughout their range in Washington, Oregon, and California south to San Francisco Bay. In that model, amount and pattern of nesting habitat made the strongest contribution to predictions of spatial distribution and temporal trends of murrelet populations at sea; marine factors such as sea surface temperature and chlorophyll, as well as ENSO and PDO indices, had little effect. Murrelet nesting habitat seems to be the primary driver of murrelet population status and trend, at least in recent decades, but that relationship has not been tested empirically and a cause-effect relationship has not been established. Raphael et al (2016b) suggest that one test of this relationship will be whether murrelet populations are observed to increase when the net amount of suitable nesting habitat increases at some point in the future.

The fundamental assumptions of the NWFP were that the rate of loss of murrelet nesting habitat in reserves would slow or stop, and that unsuitable forest cover types would recover. Available data support this assumption and show that rates of loss on NWFP lands are low, and that forest stands in reserves are on a trajectory toward higher nesting habitat suitability. Conservation and restoration of murrelet nesting habitat are essential to population viability of the species.

Although federal protection of nesting habitat is essential to murrelet viability, it may not be sufficient given the cumulative effects of other influences on population viability. Research has documented that murrelet viability depends on a variety of factors, many of which (e.g., supply of ocean prey) are not under the control or influence of the NWFP. Nesting habitat loss on nonfederal lands, marine conditions, and threats from disease, oil spills, and gillnetting could reduce the likelihood of population viability despite the habitat protections built into the NWFP. Past timber harvest was hypothesized to have lingering effects on murrelet carrying capacity and nesting success. We are aware of no new data to challenge this hypothesis. Recent research shows that murrelet population size is reduced as nesting habitat is lost, and that birds do not pack into remaining suitable nesting habitat (Burger 2001, Raphael et al. 2002a).

A major premise of the NWFP is that large reserves will support more murrelets, eventually leading to stationary or increasing populations. Because of the long period of time required to recruit new nesting habitat in reserves, thus forming larger blocks of nesting habitat, it is too soon to fully evaluate this premise, but trends on Forest Service lands in the Oregon Coast Range suggest that this may be starting to occur there.

Fahrig (1997) suggested that habitat loss tends to far outweigh the spatial configuration of habitat (fragmentation) as a risk to species. Although habitat loss and limitation appear to best explain the observed patterns of murrelet distribution and population trends in the Plan area, spatial configuration of nesting habitat is also a factor. As discussed above (see "Landscape-level relationships between nesting habitat and populations"), fragmentation of nesting habitat and the associated greater amounts of habitat edge may increase the risk of breeding failure due to nest predation.

Also, as summarized above, nest depredation seems to be a major limiting factor on murrelet populations, and nesting habitat configuration may affect predation risk. More than half of known murrelet nests whose fate has been determined failed because eggs or chicks were lost to predators, primarily jays, crows, and ravens (Manley and Nelson 1999, and other papers cited above). The relationship of predation risk and forest configuration appears to be complex. Increased edge resulting from forest fragmentation appears to have negative effects on murrelets. For example, some research has found higher densities of nest predators near edges (primarily jays), particularly where edges are near human development such as campgrounds (Goldenberg 2013, Marzluff and Neatherlin 2006) or include berry-producing plants (Masselink 2001). Other research suggests that predator numbers are high in old-growth forests with complex forest structure, such as those expected to develop in NWFP reserves, but lower in mature forests with simpler structure (Marzluff et al. 2000, Raphael et al. 2002b). At the plot scale (90 to 260 ac), one study found predator densities higher and nest success lower in plots with a variety of tree ages intermixed with young tree/brush habitats (Luginbuhl et al. 2001). The relationship between nest predator density and predation risk may also depend on the scale of observation. Luginbuhl and others (2001) found that nest predation risk was much better predicted by corvid abundance at the landscape level (2 to 20 mi^2 [5 to 52 km^2] scale) than at a finer scale (60 to 120 ac [24 to 49 km^2]), likely because of the large home range of some corvids (ravens, crows).

Forest fragmentation will decline as young patches within reserves mature, creating more contiguous canopy cover, and where rates of nest predation would decrease as forests became less fragmented. Murrelet populations may not grow at the rate predicted from recovery of nesting habitat in reserves because nest depredation could suppress successful reproduction. We lack understanding of the full suite of factors that affect nest success, which increases uncertainty about the relations between amounts of nesting habitat and murrelet populations.

Research indicates that maintaining older, maturing forest adjacent to nesting habitat also reduces predation risk (table 5-6). Taken as a whole, research to date suggests that, apart from increasing the amount of nesting habitat and reducing its fragmentation, managing forest structure to reduce nest predation risk should be approached with consideration of local factors that might affect predator densities (e.g., overstory thinning that might result in increased abundance of berry-producing early-seral shrubs that attract corvids).

Although habitat loss and fragmentation lead as factors influencing murrelet numbers and trends, birds in the NWFP area are also affected by marine factors. Murrelets are subject to risk from large oil spills at sea, which killed an estimated 872 to 2,024 murrelets between 1977 and 2008 in California, Oregon, and Washington, and continue to be a threat, as they can cause severe localized impacts such as direct mortality through oiling, as well as other less direct effects (USFWS 2009). Gill net mortality in the Plan area has been reduced substantially since 1994, with California and Oregon banning gill net use near shore, and measures taken in Washington to reduce seabird mortality (McShane et al. 2004, USFWS 2009). As discussed above ("Marine Habitat," "Changes in foraging habitat conditions," and "Climate Change Considerations"), murrelet reproductive success is influenced by prey quality and availability, which can be affected by fishing as well as changes in ocean conditions, including those linked to climate change. Future energy development, both at sea and on land, could also pose a local threat to murrelets, such as potential collisions with wind turbines (USFWS 2009).

Cumulative effects—

Wildlife population trends reflect the cumulative effects of multiple interacting factors. Nesting habitat conditions on federal lands are but one of those factors, albeit the one over which the NWFP has the most direct influence. Monitoring both nesting habitat trends and population trends is of value: monitoring nesting habitat trends tells managers how well the Plan is meeting its primary objectives; monitoring population trends tells managers if the NWFP is having the desired effects. Ideally, population trends will track nesting habitat trends, but we may observe diverging trends. In such cases, we can dig deeper to discover whether our understanding of nesting habitat relationships is mistaken or whether other, perhaps unmeasured, factors are driving population trends. Research to date, as noted above, does support the idea that population trends track nesting habitat trends, but the evidence is still based on correlations and has not established cause-effect relationships.

Carrying capacity is a measure of the potential population size that can be supported by a given amount and distribution of suitable nesting habitat. The actual population may be lower than the carrying capacity owing to a variety of other factors such as hostile weather, interactions with other species, nesting habitat conditions outside of the planning area, disease, or other factors that might depress a population. Observing a declining population in the face of habitat conservation does not mean that habitat is not important or that habitat conservation is not important. It means we have to look at options to manage some of the other factors that might be driving the population trend. Until we have more robust models of wildlife habitat relationships, which include these other factors, continued monitoring of both population and habitat trends will be important to evaluate how well the NWFP is meeting its intended objectives.

Efficacy of large reserves for murrelet conservation— A central tenet of the NWFP was that the system of large, late-successional reserves would largely suffice to provide for species and biodiversity components associated with late-successional and old-growth forest ecosystems. We have found that, to an extent, this is true with respect to murrelets. However, the degree to which late-successional reserves—along with the set of other NWFP land allocations (e.g., riparian reserves in matrix lands)—suffice differs considerably by species. Our review has highlighted the importance of large contiguous blocks of nesting habitat in meeting the nesting needs of the murrelet, and reserves seem an essential way to create such landscapes.

One of the management dilemmas is that optimal habitat conditions differ among species. Creating shrubby foraging habitat will be good for the northern spotted owl in the southern parts of its range, but such habitat will also be good for jays and crows, which depredate nests of the murrelet. In this case, what is good for the owl may be bad for the murrelet (see chapter 12 for further discussion of interactions among NWFP goals and objectives).

Management Considerations

Some key points emerge from this synthesis:

- Maintaining and increasing the area and cohesion (creating larger blocks) of suitable nesting-habitat area on federal lands will likely contribute to stabilizing and eventually recovering murrelet populations. Within NWFP lands, the current NWFP reserve system (including riparian buffers and other set-asides) appears well designed to accomplish this. Because it can take many decades for murrelet nesting habitat to develop, protection of existing habitat for the next several decades will continue to be key to minimizing habitat losses, both within and outside of reserves.
- Defining the inland limit of the murrelet nesting range will require additional survey work and a synthesis of existing observations. A refined range will better meet management objectives and avoid problems with managing for murrelets in areas where none are really expected to exist.
- Conservation of existing nesting habitat on federal lands may not be sufficient to conserve murrelet populations in the short term. Contributions from nonfederal lands may help the NWFP or its successor to achieve objectives for the murrelet, and the larger goal of murrelet conservation and recovery. This might be approached by collaborative programs to increase murrelet conservation on nonfederal lands, particularly those adjacent to NWFP lands, and in key areas (such as southwest Washington and northwest Oregon) where few federal reserves exist.
- Restoration of old-forest/murrelet nesting habitat in reserves may be accelerated by active management toward that end. Active management actions could include thinning in plantations to accelerate growth of potential nest trees and development of nesting platforms, but care will be needed to prevent simultaneously increasing numbers of nest predators attracted to more diverse understory conditions. Moreover, such management should also be careful to not increase the suitability of older forests to harbor barred owls (*Strix varia*), which may prey on murrelets and also reduce forest suitability for northern spotted owls (see chapter 4). Development and implementation of forest management practices that protect (short term) and develop (long term, e.g., over many decades) suitable murrelet nesting habitat on NWFP lands within the murrelet range would be beneficial in recovering murrelet populations (see chapter 3 for examples of restoration treatments).
- To guide management and increase its effectiveness in achieving nesting habitat expansion, modeling tools are needed to help forecast site-specific future nesting habitat development and structural characteristics of potential murrelet nesting habitat.

- Restoration in plantations and younger natural forests can benefit murrelets by incorporating an understanding of relations among stand shape, extent of higher-contrast edges, and populations of potential nest predators, including corvids. Proximity of nest and occupied habitat should be considered. Treatments that consider risk to existing suitable nesting habitat along exposed edges from windthrow would also contribute to conservation of existing nesting habitat.
- Forest planning and management can positively affect murrelet status by managing human recreation activities that might promote murrelet nest predator populations (e.g., ravens, crows, and jays in campgrounds). The greatest benefit would be expected in areas within and near existing and developing murrelet nesting habitat. Implementing education programs, limiting garbage, and controlling predators could have positive effects.
- Future management and design of reserves will benefit from accounting for climate change, including increased risks to murrelet nesting habitat from fire and other natural disturbances. Boundaries of reserves (including making them larger) may be reconsidered if revised boundaries might better conserve nesting habitat in the face of anticipated effects of climate change.
- Maintaining a broad distribution of large nesting habitat blocks over the NWFP landscape will likely help to minimizing the risk to the population from nesting habitat loss to fire, wind or other disturbance agents.

The NWFP remains the boldest effort ever undertaken by federal agencies to meet large-scale biodiversity objectives. The Plan had a short-term objective for murrelets: conserve much of the best remaining nesting habitat. The NWFP has been very successful in meeting this objective. The NWFP also has a long-term objective: create a system of reserves containing desired sizes and distributions of large blocks for suitable nesting habitat. Evidence suggests that nesting habitat trends on federal lands are on course toward this objective, but many more decades will be needed to observe whether the Plan is successful in achieving its goal to stabilize and increase murrelet populations by maintaining and increasing nesting habitat. We have shown that the NWFP has been remarkably successful in conserving nesting habitat over its first 20 years of implementation, but much work remains. Murrelet numbers continue to decline in the northern portion of the Plan area. Assuming no large fires, we believe that the current decline in amount of murrelet nesting habitat will reverse on federal lands, leading to a net increase in the amount of nesting habitat, and that murrelet populations should also increase in response. How many decades before this reversal in trend occurs is unknown, but at-sea monitoring suggests that the first step of possible population stabilization may be occurring in the southern Plan area. Lastly, climate change has emerged as an external force that may affect future murrelet populations, their nesting habitat, and, in particular, food resources for murrelets.

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Metric Equivalents

When you know:	Multiply by:	To find:
Feet (ft)	0.3049	Meters
Miles (mi)	1.61	Kilometers
Acres (ac)	0.4049	Hectares
Square miles (mi^2)	2.59	Square kilometers

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Scientific and common names of plant species identified in this report

Scientific name	Common name
Abies amabilis (Douglas ex Loudon) Douglas ex Forbes	Pacific silver fir
Abies concolor (Gord. & Glend.) Lindl. ex Hildebr.	White fir
Abies grandis (Douglas ex D. Don) Lindl.	Grand fir
Abies lasiocarpa (Hook.) Nutt.	Subalpine pine
Abies magnifica A. Murray bis	California red fir
Abies procera Rehder	Noble fir
Acer circinatum Pursh	Vine maple
Acer macrophyllum Pursh	Bigleaf maple
Achlys triphylla (Sm.) DC.	Sweet after death
Adenocaulon bicolor Hook.	American trailplant
Alliaria petiolata (M. Bieb.) Cavara & Grande	Garlic mustard
Alnus rubra Bong.	Red alder
Amelanchier alnifolia (Nutt.) Nutt. ex M. Roem.	Saskatoon serviceberry
Anemone oregana A. Gray	Blue windflower
Apocynum cannabinum L.	Dogbane
Arbutus menziesii Pursh)	Madrone
Arceuthobium M. Bieb.	Dwarf mistletoe
Arceuthobium occidentale Engelm.	Gray pine dwarf mistletoe
Arceuthobium tsugense Rosendahl	Hemlock dwarf mistletoe
Arctostaphylos nevadensis A. Gray	Pinemat manzanita
Brachypodium sylvaticum (Huds.) P. Beauv.	False brome
Brodiaea coronaria (Salisb.) Engl.	Cluster-lilies
Callitropsis nootkatensis (D. Don) Oerst. ex D.P. Little	Alaska yellow-cedar
Calocedrus decurrens (Torr.) Florin	Incense cedar
Cannabis L.	Marijuana
Carex barbarae Dewey and *C. obnupta* L.H. Bailey	Sedges
Centaurea solstitialis L.	Yellow starthistle
Chamaecyparis lawsoniana (A. Murray bis) Parl.	Port Orford cedar
Chimaphila menziesii (R. Br. ex D. Don) Spreng.	Little prince's pine
Chimaphila umbellata (L.) W.P.C. Barton	Pipsissewa
Clematis vitalba L.	Old man's beard
Clintonia uniflora Menzies ex Schult. & Schult. f.) Kunth	Bride's bonnet
Coptis laciniata A. Gray	Oregon goldthread
Corylus cornuta Marshall var. *californica* (A. DC.) Sharp	California hazel
Cornus canadensis L.	Bunchberry dogwood
Cytisus scoparius (L.) Link	Scotch broom
Disporum hookeri (Torr.) G. Nicholson var. *hookeri*	Drops-of-gold
Fallopia japonica (Houtt.) Ronse Decr. var. *japonica*	Japanese knotweed
Gaultheria ovatifolia A. Gray	Western teaberry
Gaultheria shallon Pursh	Salal

Scientific name	Common name
Gentiana douglasiana Bong.	Swamp gentian
Geranium lucidum L.	Shining geranium
Geranium robertianum L.	Robert geranium
Goodyera oblongifolia Raf.	Western rattlesnake plantain
Hedera helix L.	English ivy
Heracleum mantegazzianum Sommier & Levier	Giant hogweed
Hesperocyparis sargentii (Jeps.) Bartel	Sargent's cypress
Hieracium aurantiacum L.	Orange hawkweed
Ilex aquifolium L.	English holly
Iris pseudacorus L.	Paleyellow iris
Juniperus occidentalis Hook.	Western juniper
Lamiastrum galeobdolon (L.) Ehrend. & Polatschek	Yellow archangel
Lilium occidentale Purdy	Western lily
Linnaea borealis L.	Twinflower
Lithocarpus densiflorus (Hook. & Arn.) Rehder	Tanoak
Lonicera hispidula Pursh	Honeysuckle
Lupinus albicaulis Douglas	Sickle-keeled lupine
Lycopodium clavatum L.	Running clubmoss
Lythrum salicaria L.	Purple loosestrife
Mahonia nervosa (Pursh) Nutt.	Cascade barberry
Malus fusca (Raf.) C.K. Schneid.	Pacific crabapple
Notholithocarpus densiflorus (Hook. & Arn.) P.S. Manos, C.H. Cannon, & S.H. Oh	Tanoak
Notholithocarpus densiflorus (Hook. & Arn.) P.S. Manos, C.H. Cannon, & S.H. Oh var. *echinoides* (R.Br. ter) P.S. Manos, C.H. Cannon & S.H. Oh	Shrub form of tanoak
Nuphar polysepala (Engelm.)	Yellow pond lily
Nymphoides peltata (S.G. Gmel.) Kuntze	Yellow floating heart
Osmorhiza chilensis Hook. & Arn.	Sweetcicely
Phalaris arundinacea L.	Reed canarygrass
Picea engelmannii Parry ex Engelm.	Engelmann spruce
Picea sitchensis (Bong.) Carrière	Sitka spruce
Pinus albicaulis Engelm.	Whitebark pine
Pinus attenuata Lemmon	Knobcone pine
Pinus contorta Douglas ex Loudon	Lodgepole pine
Pinus contorta Douglas ex Loudon var. *contorta*	Beach pine, shore pine
Pinus jeffreyi Balf.	Jeffrey pine
Pinus lambertiana Douglas	Sugar pine
Pinus monticola Douglas ex D. Don)	Western white pine
Pinus ponderosa Lawson & C. Lawson	Ponderosa pine
Populus trichocarpa L. ssp. *trichocarpa* (Torr. & A. Gray ex Hook) Brayshaw	Black cottonwood
Potamogeton crispus L.	Curly pondweed
Potentilla recta L.	Sulphur cinquefoil

Scientific name	**Common name**
Prunus emarginata (Douglas ex Hook. D. Dietr.)	Bitter cherry
Pseudotsuga menziesii (Mirb.) Franco	Douglas-fir
Pteridium aquilinum (L. Kuhn)	Brackenfern
Pueraria montana (Lour.) Merr. var. *lobata* (Willd.) Maesen & S.M. Almeida ex Sanjappa & Predeep	Kudzu
Pyrola asarifolia Sweet	American wintergreen
Quercus agrifolia Née var. *oxyadenia* (Torr.) J.T. Howell	Coastal live oak
Quercus berberidifolia Liebm.	Scrub oak
Quercus chrysolepis Liebm.	Canyon live oak
Quercus douglasii Hook. & Arn.	Blue oak
Quercus garryana Douglas ex hook.	Oregon white oak
Quercus kelloggi Newberry	California black oak
Quercus lobata Née	Valley oak
Rhamnus purshiana (DC.) A. Gray	Cascara
Rhododendron groenlandicum Oeder	Bog Labrador tea
Rhododendron macrophyllum D. Don ex G. Don	Pacific rhododendron
Ribes lacustre (Pers.) Poir.	Prickly currant
Rubus armeniacus Focke	Himalayan blackberry
Salix exigua Nutt.	Sandbar willow
Senecio bolanderi A. Gray	Bolander’s ragwort
Sequoia sempervirens (Lamb. ex D. Don) Endl.	Redwood
Smilacina stellata (L.) Desf.	Starry false Solomon’s seal
Synthyris reniformis (Douglas ex Benth.) Benth.	Snowqueen
Taxus brevifolia Nutt.	Pacific yew
Thuja plicata Donn ex D. Don	Western redcedar
Tiarella trifoliate L.	Threeleaf foamflower
Trapa natans L.	Water chestnut
Trillium ovatum Pursh	Pacific trillium
Tsuga heterophylla (Raf.) Sarg.	Western hemlock
Tsuga mertensiana (Bong.) Carrière	Mountain hemlock
Typha latifolia L.	Cattails
Umbellularia californica (Hook. & Arn.) Nutt.	California bay laurel
Vaccinium alaskaense Howell	Alaska blueberry
Vaccinium membranaceum Douglas ex Torr.	Thinleaf huckleberry, big huckleberry
Vaccinium ovatum Pursh	Evergreen huckleberry
Vaccinium oxycoccos L.	Small cranberry
Vaccinium parvifolium Sm.	Red huckleberry
Vancouveria hexandra (Hook.) C. Morren & Decne.	White insideout flower
Xerophyllum tenax (Pursh) Nutt.	Beargrass

Glossary

This glossary is provided to help readers understand various terms used in the Northwest Forest Plan (NWFP) science synthesis. Sources include the Forest Service Handbook (FSH), the Code of Federal Regulations (CFR), executive orders, the Federal Register (FR), and various scientific publications (see "Glossary Literature Cited"). The authors have added working definitions of terms used in the synthesis and its source materials, especially when formal definitions may be lacking or when they differ across sources.

active management—Direct interventions to achieve desired outcomes, which may include harvesting and planting of vegetation and the intentional use of fire, among other activities (Carey 2003).

adaptive capacity—The ability of ecosystems and social systems to respond to, cope with, or adapt to disturbances and stressors, including environmental change, to maintain options for future generations (FSH 1909.12.5).

adaptive management—A structured, cyclical process for planning and decisionmaking in the face of uncertainty and changing conditions with feedback from monitoring, which includes using the planning process to actively test assumptions, track relevant conditions over time, and measure management effectiveness (FSH 1909.12.5). Additionally, adaptive management includes iterative decisionmaking, through which results are evaluated and actions are adjusted based on what has been learned.

adaptive management area (AMA)—A portion of the federal land area within the NWFP area that was specifically allocated for scientific monitoring and research to explore new forestry methods and other activities related to meeting the goals and objectives of the Plan. Ten AMAs were established in the NWFP area, covering about 1.5 million ac (600 000 ha), or 6 percent of the planning area (Stankey et al. 2003).

alien species—Any species, including its seeds, eggs, spores, or other biological material capable of propagating that species, that is not native to a particular ecosystem (Executive Order 13112). The term is synonymous with exotic species, nonindigenous, and nonnative species (see also "invasive species").

allochthonous inputs—Material, specifically food resources, that originates from outside a stream, typically in the form of leaf litter.

amenity communities—Communities located near lands with high amenity values.

amenity migration—Movement of people based on the draw of natural or cultural amenities (Gosnell and Abrams 2011).

amenity value—A noncommodity or "unpriced" value of a place or environment, typically encompassing aesthetic, social, cultural, and recreational values.

ancestral lands (of American Indian tribes)—Lands that historically were inhabited by the ancestors of American Indian tribes.

annual species review—A procedure established under the NWFP in which panels of managers and biologists evaluate new scientific and monitoring information on species to potentially support the recommendation of changes in their conservation status.

Anthropocene—The current period (or geological epoch) in which humans have become a dominant influence on the Earth's climate and environment, generally dating from the period of rapid growth in industrialization, population, and global trade and transportation in the early 1800s (Steffen et al. 2007).

Aquatic Conservation Strategy (ACS) —A regional strategy applied to aquatic and riparian ecosystems across the area covered by the NWFP) (Espy and Babbit 1994) (see chapter 7 for more details).

at-risk species—Federally recognized threatened, endangered, proposed, and candidate species and species of conservation concern. These species are considered at risk of low viability as a result of changing environmental conditions or human-caused stressors.

best management practices (BMPs) (for water quality)—Methods, measures, or practices used to reduce or eliminate the introduction of pollutants and other detrimental impacts to water quality, including but not limited to structural and nonstructural controls and to operation and maintenance procedures.

biodiversity—In general, the variety of life forms and their processes and ecological functions, at all levels of biological organization from genes to populations, species, assemblages, communities, and ecosystems.

breeding inhibition—Prevention of reproduction in healthy adult individuals.

bryophytes—Mosses and liverworts.

canopy cover—The downward vertical projection from the outside profile of the canopy (crown) of a plant measured in percentage of land area covered.

carrying capacity—The maximum population size a specific environment can sustain.

ceded areas—Lands that particular tribes ceded to the United States government by treaties, which have been catalogued in the Library of Congress.

climate adaptation—Management actions to reduce vulnerabilities to climate change and related disturbances.

climate change—Changes in average weather conditions (including temperature, precipitation, and risk of certain types of severe weather events) that persist over multiple decades or longer, and that result from both natural factors and human activities such as increased emissions of greenhouse gases (U.S. Global Change Research Program 2017).

coarse filter—A conservation approach that focuses on conserving ecosystems, in contrast to a "fine filter" approach that focuses on conserving specific species. These two approaches are generally viewed as complementary, with fine-filtered strategies tailored to fit particular species that "fall through the pores" of the coarse filter (Hunter 2005). See also "mesofilter."

co-management—Two or more entities, each having legally established management responsibilities, working collaboratively to achieve mutually agreed upon, compatible objectives to protect, conserve, use, enhance, or restore natural and cultural resources (81 FR 4638).

collaborative management—Two or more entities working together to actively protect, conserve, use, enhance, or restore natural and cultural resources (81 FR 4638).

collaboration or collaborative process—A structured manner in which a collection of people with diverse interests share knowledge, ideas, and resources, while working together in an inclusive and cooperative manner toward a common purpose (FSH 1909.12.05).

community (plant and animal)—A naturally occurring assemblage of plant and animal species living within a defined area or habitat (36 CFR 219.19).

community forest—A general definition is forest land that is managed by local communities to provide local benefits (Teitelbaum et al. 2006). The federal government has specifically defined community forest as "forest land owned in fee simple by an eligible entity [local government, nonprofit organization, or federally recognized tribe] that provides public access and is managed to provide community benefits pursuant to a community forest plan" (36 CFR 230.2).

community of place or place-based community—A group of people who are bound together because of where they reside, work, visit, or otherwise spend a continuous portion of their time.

community resilience—The capacity of a community to return to its initial function and structure when initially altered under disturbance.

community resistance—The capacity of a community to withstand a disturbance without changing its function and structure.

composition—The biological elements within the various levels of biological organization, from genes and species to communities and ecosystems (FSM 2020).

congeneric—Organisms that belong to the same taxonomic genus, usually belonging to different species.

connectivity (of habitats)—Environmental conditions that exist at several spatial and temporal scales that provide landscape linkages that permit (a) the exchange of flow, sediments, and nutrients; (b) genetic interchange of genes among individuals between populations; and (c) the long-distance range shifts of species, such as in response to climate change (36 CFR 219.19).

consultation (tribal)—A formal government-to-government process that enables American Indian tribes and Alaska Native Corporations to provide meaningful, timely input, and, as appropriate, exchange views, information, and recommendations on proposed policies or actions that may affect their rights or interests prior to a decision. Consultation is a unique form of communication characterized by trust and respect (FSM 1509.05).

corticosterone—A steroid hormone produced by many species of animals, often as the result of stress.

cryptogam—An organism that reproduces by spores and that does not produce true flowers and seeds; includes fungi, algae, lichens, mosses, liverworts, and ferns.

cultural keystone species—A species that significantly shapes the cultural identity of a people, as reflected in diet, materials, medicine, or spiritual practice (Garibaldi and Turner 2004).

cultural services—A type of ecosystem service that includes the nonmaterial benefits that people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences (Sarukhán and Whyte 2005).

desired conditions—A description of specific social, economic, or ecological characteristics toward which management of the land and resources should be directed.

disturbance regime—A description of the characteristic types of disturbance on a given landscape; the frequency, severity, and size distribution of these characteristic disturbance types and their interactions (36 CFR 219.19).

disturbance—Any relatively discrete event in time that disrupts ecosystem, watershed, community, or species population structure or function, and that changes resources, substrate availability, or the physical environment (36 CFR 219.19).

dynamic reserves—A conservation approach in which protected areas are relocated following changes in environmental conditions, especially owing to disturbance.

early-seral vegetation—Vegetation conditions in the early stages of succession following an event that removes the forest canopy (e.g., timber harvest, wildfire, windstorm), on sites that are capable of developing a closed canopy (Swanson et al. 2014). A nonforest or "pre-forest" condition occurs first, followed by an "early-seral forest" as young shade-intolerant trees form a closed canopy.

ecocultural resources—Valued elements of the biophysical environment, including plants, fungi, wildlife, water, and places, and the social and cultural relationships of people with those elements.

ecological conditions—The biological and physical environment that can affect the diversity of plant and animal communities, the persistence of native species, invasibility, and productive capacity of ecological systems. Ecological conditions include habitat and other influences on species and the environment. Examples of ecological conditions include the abundance and distribution of aquatic and terrestrial habitats, connectivity, roads and other structural developments, human uses, and occurrence of other species (36 CFR 219.19).

ecological forestry—A ecosystem management approach designed to achieve multiple objectives that may include conservation goals and sustainable forest management and which emphasizes disturbance-based management and retention of "legacy" elements such as old trees and dead wood (Franklin et al. 2007).

ecological integrity—The quality or condition of an ecosystem when its dominant ecological characteristics (e.g., composition, structure, function, connectivity, and species composition and diversity) occur within the natural range of variation and can withstand and recover from most perturbations imposed by natural environmental dynamics or human influence (36 CFR 219.19).

ecological keystone species—A species whose ecological functions have extensive and disproportionately large effects on ecosystems relative to its abundance (Power et al. 1996).

ecological sustainability—The capability of ecosystems to maintain ecological integrity (36 CFR 219.19).

economic sustainability—The capability of society to produce and consume or otherwise benefit from goods and services, including contributions to jobs and market and nonmarket benefits (36 CFR 219.19).

ecoregion—A geographic area containing distinctive ecological assemblages, topographic and climatic gradients, and historical land uses.

ecosystem—A spatially explicit, relatively homogeneous unit of the Earth that includes all interacting organisms and elements of the abiotic environment within its boundaries (36 CFR 219.19).

ecosystem diversity—The variety and relative extent of ecosystems (36 CFR 219.19).

ecosystem integrity—See "ecological integrity."

ecosystem management—Management across broad spatial and long temporal scales for a suite of goals, including maintaining populations of multiple species and ecosystem services.

ecosystem services—Benefits that people obtain from ecosystems (see also "provisioning services," "regulating services," "supporting services," and "cultural services").

ectomycorrhizal fungi—Fungal species that form symbiotic relationships with vascular plants through roots, typically aiding their uptake of nutrients. Although other mycorrhizal fungi penetrate their host's cell walls, ectomycorrhizal fungi do not.

endangered species—Any species or subspecies that the Secretary of the Interior or the Secretary of Commerce has deemed in danger of extinction throughout all or a significant portion of its range (16 U.S.C. Section 1532).

endemic—Native and restricted to a specific geographical area.

El Niño Southern Oscillation (ENSO)—A band of anomalously warm ocean water temperatures that occasionally develops off the western coast of South America and can cause climatic changes across the Pacific Ocean. The extremes of this climate pattern's oscillations cause extreme weather (such as floods and droughts) in many regions of the world.

environmental DNA (eDNA)—Genetic material (DNA) contained within small biological and tissue fragments that can be collected from aquatic, terrestrial, and even atmospheric environments, linked to an individual species, and used to indicate the presence of that species.

environmental justice populations—Groups of people who have low incomes or who identify themselves as African American, Asian or Pacific Islander, American Indian or Alaskan Native, or of Hispanic origin.

ephemeral stream—A stream that flows only in direct response to precipitation in the immediate locality (watershed or catchment basin), and whose channel is at all other times above the zone of saturation.

epicormic—Literally, "of a shoot or branch," this term implies growth from a previously dormant bud on the trunk or a limb of a tree.

epiphyte—A plant or plant ally (including mosses and lichens) that grows on the surface of another plant such as a tree, but is not a parasite.

even-aged stand—A stand of trees composed of a single age class (36 CFR 219.19).

fecundity—The reproductive rate of an organism or population.

federally recognized Indian tribe—An Indian tribe or Alaska Native Corporation, band, nation, pueblo, village, or community that the Secretary of the Interior acknowledges to exist as an Indian tribe under the Federally Recognized Indian Tribe List Act of 1994, 25 U.S.C. 479a (36 CFR 219.19).

fine filter—A conservation approach that focuses on conserving individual species in contrast to a "coarse filter" approach that focuses on conserving ecosystems; these approaches are generally viewed as complementary with fine-filtered strategies tailored to fit particular species that "fall through the pores" of the coarse filter (Hunter 2005). See also "mesofilter."

fire-dependent vegetation types—A vegetative community that evolved with fire as a necessary contributor to its vitality and to the renewal of habitat for its member species.

fire exclusion—Curtailment of wildland fire because of deliberate suppression of ignitions, as well as unintentional effects of human activities such as intensive grazing that removes grasses and other fuels that carry fire (Keane et al. 2002).

fire intensity—The amount of energy or heat release during fire.

fire regime—A characterization of long-term patterns of fire in a given ecosystem over a specified and relatively long period of time, based on multiple attributes, including frequency, severity, extent, spatial complexity, and seasonality of fire occurrence.

fire regime, low frequency, high severity—A fire regime with long return intervals (>200 years) and high levels of vegetation mortality (e.g., ~70 percent basal area mortality in forested ecosystems), often occurring in large patches (>10,000 ac [4047 ha]) (see chapter 3 for more details).

fire regime, moderate frequency, mixed severity—A fire regime with moderate return intervals between 50 and 200 years and mixtures of low, moderate, and high severity; high-severity patches would have been common and frequently large (>1,000 ac [>405 ha]) (see chapter 3 for more details).

fire regime, very frequent, low severity—A fire regime with short return intervals (5 to 25 years) dominated by surface fires that result in low levels of vegetation mortality (e.g., <20 percent basal area mortality in forested ecosystems), with high-severity fire generally limited to small patches (<2.5 ac [1 ha]) (see chapter 3 for more details).

fire regime, frequent, mixed severity—A fire regime with return intervals between 15 and 50 years that burns with a mosaic of low-, moderate-, and high-severity patches (Perry et al. 2011) (see chapter 3 for more details).

fire rotation—Length of time expected for a specific amount of land to burn (some parts might burn more than once or some not at all) based upon the study of past fire records in a large landscape (Turner and Romme 1994).

fire severity—The magnitude of the effects of fire on ecosystem components, including vegetation or soils.

fire suppression—The human act of extinguishing wildfires (Keane et al. 2002).

floodplain restoration—Ecological restoration of a stream or river's floodplain, which may involve setback or removal of levees or other structural constraints.

focal species—A small set of species whose status is assumed to infer the integrity of the larger ecological system to which it belongs, and thus to provide meaningful information regarding the effectiveness of a resource management plan in maintaining or restoring the ecological conditions to maintain the broader diversity of plant and animal communities in the NWPF area. Focal species would be commonly selected on the basis of their functional role in ecosystems (36 CFR 219.19).

food web—Interconnecting chains between organisms in an ecological community based upon what they consume.

Forest Ecosystem Management Assessment Team (FEMAT)—An interdisciplinary team that included expert ecological and social scientists, analysts, and managers assembled in 1993 by President Bill Clinton to develop options for ecosystem management of federal forests within the range of the northern spotted owl (FEMAT 1993).

forest fragmentation—The patterns of dispersion and connectivity of nonhomogeneous forest cover (Riitters et al. 2002). See also “landscape fragmentation” and “habitat fragmentation” for specific meanings related to habitat loss and isolation.

frequency distribution—A depiction, often appearing in the form of a curve or graph, of the abundance of possible values of a variable. In this synthesis report, we speak of the frequency of wildfire patches of various sizes.

fuels (wildland)—Combustible material in wildland areas, including live and dead plant biomass such as trees, shrub, grass, leaves, litter, snags, and logs.

fuels management—Manipulation of wildland fuels through mechanical, chemical, biological, or manual means, or by fire, in support of land management objectives to control or mitigate the effects of future wildland fire.

function (ecological)—Ecological processes, such as energy flow; nutrient cycling and retention; soil development and retention; predation and herbivory; and natural disturbances such as wind, fire, and floods that sustain composition and structure (FSM 2020). See also “key ecological function.”

future range of variation (FRV)—The natural fluctuation of pattern components of healthy ecosystems that might occur in the future, primarily affected by climate change, human infrastructure, invasive species, and other anticipated disturbances.

gaps (forest)—Small openings in a forest canopy that are naturally formed when one or a few canopy trees die (Yamamoto 2000).

genotype—The genetic makeup of an individual organism.

glucocorticoid—A class of steroid hormones produced by many species of animals, often as the result of stress.

goals (in land management plans)—Broad statements of intent, other than desired conditions, that do not include expected completion dates (36 CFR part 219.7(e)(2)).

guideline—A constraint on project and activity decision-making that allows for departure from its terms, so long as the purpose of the guideline is met (36 CFR section 219.15(d)(3)). Guidelines are established to help achieve or maintain a desired condition or conditions, to avoid or mitigate undesirable effects, or to meet applicable legal requirements.

habitat—An area with the environmental conditions and resources that are necessary for occupancy by a species and for individuals of that species to survive and reproduce.

habitat fragmentation—Discontinuity in the spatial distribution of resources and conditions present in an area at a given scale that affects occupancy, reproduction, and survival in a particular species (see “landscape fragmentation”).

heterogeneity (forest)—Diversity, often applied to variation in forest structure within stands in two dimensions: horizontal (e.g., single trees, clumps of trees, and gaps of no trees), and vertical (e.g., vegetation at different heights from the forest floor to the top of the forest canopy), or across large landscapes (North et al. 2009).

hierarchy theory—A theory that describes ecosystems at multiple levels of organization (e.g., organisms, populations, and communities) in a nested hierarchy.

high-severity burn patch—A contiguous area of high-severity or stand-replacing fire.

historical range of variation (HRV)—Past fluctuation or range of conditions in the pattern of components of ecosystems over a specified period of time.

hybrid ecosystem—An ecosystem that has been modified from a historical state such that it has novel attributes while retaining some original characteristics (see “novel ecosystem”).

hybrid—Offspring resulting from the breeding of two different species.

inbreeding depression—Reduced fitness in a population that occurs as the result of breeding between related individuals, leading to increased homogeneity and simplification of the gene pool.

in-channel restoration—Ecological restoration of the channel of a stream or river, often through placement of materials (rocks and wood) or other structural modifications.

individuals, clumps, and openings (ICO) method—A method that incorporates reference spatial pattern targets based upon individual trees, clumps of trees, and canopy openings into silvicultural prescriptions and tree-marking guidelines (Churchill et al. 2013).

Interagency Special Status and Sensitive Species Program (ISSSSP)—A federal agency program, established under the U.S. Forest Service Pacific Northwest Region and Bureau of Land Management Oregon/Washington state office. The ISSSSP superseded the Survey and Manage standards and guidelines under the NWFP and also addresses other species of conservation focus, coordinates development and revision of management recommendations and survey protocols, coordinates data management between the agencies, develops summaries of species biology, and conducts other tasks.

intermittent stream—A stream or reach of stream channel that flows, in its natural condition, only during certain times of the year or in several years, and is characterized by interspersed, permanent surface water areas containing aquatic flora and fauna adapted to the relatively harsh environmental conditions found in these types of environments.

invasive species—An alien species (or subspecies) whose deliberate, accidental, or self-introduction is likely to cause economic or environmental harm or harm to human health (Executive Order 13112).

key ecological function—The main behaviors performed by an organism that can influence environmental conditions or habitats of other species.

key watersheds—Watersheds that are expected to serve as refugia for aquatic organisms, particularly in the short term, for at-risk fish populations that have the greatest potential for restoration, or to provide sources of high-quality water.

land and resource management plan (Forest Service)—A document or set of documents that provides management direction for an administrative unit of the National Forest System (FSH 1909.12.5).

landform—A specific geomorphic feature on the surface of the Earth, such as a mountain, plateau, canyon, or valley.

landscape—A defined area irrespective of ownership or other artificial boundaries, such as a spatial mosaic of terrestrial and aquatic ecosystems, landforms, and plant communities, repeated in similar form throughout such a defined area (36 CFR 219.19).

landscape fragmentation—Breaking up of continuous habitats into patches as a result of human land use and thereby generating habitat loss, isolation, and edge effects (see “habitat fragmentation”).

landscape genetics—An interdisciplinary field of study that combines population genetics and landscape ecology to explore how genetic relatedness among individuals and subpopulations of a species is influenced by landscape-level conditions.

landscape hierarchy—Organization of land areas based upon a hierarchy of nested geographic (i.e., different-sized) units, which provides a guide for defining the functional components of a system and how components at different scales are related to one another.

late-successional forest—Forests that have developed after long periods of time (typically at least 100 to 200 years) following major disturbances, and that contain a major component of shade-tolerant tree species that can regenerate beneath a canopy and eventually grow into the canopy in which small canopy gaps occur (see chapter 3 for more details). Note that FEMAT (1993) and the NWFP also applied this term to older (at least 80 years) forest types, including both old-growth and mature forests, regardless of the shade tolerance of the dominant tree species (e.g., 90-year-old forests dominated by Douglas-fir were termed late successional).

leading edge—The boundary of a species’ range at which the population is geographically expanding through colonization of new sites.

legacy trees—Individual trees that survive a major disturbance and persist as components of early-seral stands (Franklin 1990).

legacies (biological)—Live trees, seed and seedling banks, remnant populations and individuals, snags, large soil aggregates, hyphal mats, logs, uprooted trees, and other biotic features that survive a major disturbance and persist as components of early-seral stands (Franklin 1990, Franklin et al. 2002).

lentic—Still-water environments, including lakes, ponds, and wet meadows.

longitudinal studies—Studies that include repeated observations on the same response variable over time.

lotic—Freshwater environments with running water, including rivers, streams, and springs.

low-income population—A community or a group of individuals living in geographic proximity to one another, or a set of individuals, such as migrant workers or American Indians, who meet the standards for low income and experience common conditions of environmental exposure or effect (CEQ 1997).

managing wildfire for resource objectives—Managing wildfires to promote multiple objectives such as reducing fire danger or restoring forest health and ecological processes rather than attempting full suppression. The terms "managed wildfire" or "resource objective wildfire" have also been used to describe such events (Long et al. 2017). However, fire managers note that many unplanned ignitions are managed using a combination of tactics, including direct suppression, indirect containment, monitoring of fire spread, and even accelerating fire spread, across their perimeters and over their full duration. Therefore, terms that separate "managed" wildfires from fully "suppressed" wildfires do not convey that complexity. (See "Use of wildland fire," which also includes prescribed burning).

matrix—Federal and other lands outside of specifically designated reserve areas, particularly the late-successional reserves under the NWFP, that are managed for timber production and other objectives.

mature forest—An older forest stage (>80 years) prior to old-growth in which trees begin attaining maximum heights and developing some characteristic, for example, 80 to 200 years in the case of old-growth Douglas-fir/western hemlock forests, often (but not always) including big trees (>50 cm diameter at breast height), establishment of late-seral species (i.e., shade-tolerant trees), and initiation of decadence in early species (i.e., shade-intolerant trees).

mesofilter—A conservation approach that "focuses on conserving critical elements of ecosystems that are important to many species, especially those likely to be overlooked by fine-filter approaches, such as invertebrates, fungi, and nonvascular plants" (Hunter 2005).

meta-analysis—A study that combines the results of multiple studies**.**

minority population—A readily identifiable group of people living in geographic proximity with a population that is at least 50 percent minority; or, an identifiable group that has a meaningfully greater minority population than the adjacent geographic areas, or may also be a geographically dispersed/transient set of individuals such as migrant workers or Americans Indians (CEQ 1997).

mitigation (climate change)—Efforts to reduce anthropogenic alteration of climate, in particular by increasing carbon sequestration.

monitoring—A systematic process of collecting information to track implementation (implementation monitoring), to evaluate effects of actions or changes in conditions or relationships (effectiveness monitoring), or to test underlying assumptions (validation monitoring) (see 36 CFR 219.19).

mosaic—The contiguous spatial arrangement of elements within an area. In regions, this is typically the upland vegetation patches, large urban areas, large bodies of water, and large areas of barren ground or rock. However, regional mosaics can also be described in terms of land ownership, habitat patches, land use patches, or other elements. For landscapes, this is typically the spatial arrangement of landscape elements.

multiaged stands—Forest stands having two or more age classes of trees; this includes stands resulting from variable-retention silvicultural systems or other traditionally even-aged systems that leave residual or reserve (legacy) trees.

multiple use—The management of all the various renewable surface resources of the National Forest System so that they are used in the combination that will best meet the needs of the American people; making the most judicious use of the land for some or all of these resources or related services over areas large enough to provide sufficient latitude for periodic adjustments in use to conform to changing needs and conditions; that some land will be used for less than all of the resources; and harmonious and coordinated management of the various resources, each with the other, without impairment of the productivity of the land, with consideration being given to the relative values of the various resources, and not necessarily the combination of uses that will give the greatest dollar return or the greatest unit output, consistent with the Multiple-Use Sustained-Yield Act of 1960 (16 U.S.C. 528–531) (36 CFR 219.19).

natal site—Location of birth.

native knowledge—A way of knowing or understanding the world, including traditional ecological, and social knowledge of the environment derived from multiple generations of indigenous peoples' interactions, observations, and experiences with their ecological systems. This knowledge is accumulated over successive generations and is expressed through oral traditions, ceremonies, stories, dances, songs, art, and other means within a cultural context (36 CFR 219.19).

native species—A species historically or currently present in a particular ecosystem as a result of natural migratory or evolutionary processes and not as a result of an accidental or deliberate introduction or invasion into that ecosystem (see 36 CFR 219.19).

natural range of variation (NRV)—The variation of ecological characteristics and processes over specified scales of time and space that are appropriate for a given management application (FSH 1909.12.5).

nested hierarchy—The name given to the hierarchical structure of groups within groups used to classify organisms.

nontimber forest products (also known as "special forest products")—Various products from forests that do not include logs from trees but do include bark, berries, boughs, bryophytes, bulbs, burls, Christmas trees, cones, ferns, firewood, forbs, fungi (including mushrooms), grasses, mosses, nuts, pine straw, roots, sedges, seeds, transplants, tree sap, wildflowers, fence material, mine props, posts and poles, shingle and shake bolts, and rails (36 CFR part 223 Subpart G).

novel ecosystem—An ecosystem that has experienced large and potentially irreversibly modifications to abiotic conditions or biotic composition in ways that result in a composition of species, ecological communities, and functions that have never before existed, and that depart from historical analogs (Hobbs et al. 2009). See "hybrid ecosystem" for comparison.

old-growth forest—A forest distinguished by old trees (>200 years) and related structural attributes that often (but not always) include large trees, high biomass of dead wood (i.e., snags, down coarse wood), multiple canopy layers, distinctive species composition and functions, and vertical and horizontal diversity in the tree canopy (see chapter 3). In dry, fire-frequent forests, old growth is characterized by large, old fire-resistant trees and relatively open stands without canopy layering.

palustrine—Inland, nontidal wetlands that may be permanently or temporarily flooded and are characterized by the presence of emergent vegetation such as swamps, marshes, vernal pools, and lakeshores.

passive management—A management approach in which natural processes are allowed to occur without human intervention to reach desired outcomes.

patch—A relatively small area with similar environmental conditions, such as vegetative structure and composition. Sometimes used interchangeably with vegetation or forest stand.

Pacific Decadal Oscillation (**PDO)**—A recurring (approximately decadal-scale) pattern of ocean-atmosphere —a stream or reach of a channel that flows continuously or nearly so throughout the year and whose upper surface is generally lower than the top of the zone of saturation in areas adjacent to the stream.

perennial stream—A stream or reach of a channel that flows continuously or nearly so throughout the year and whose upper surface is generally lower than the top of the zone of saturation in areas adjacent to the stream.

phenotype—Physical manifestation of the genetic makeup of an individual and its interaction with the environment.

place attachment—The "positive bond that develops between groups or individuals and their environment" (Jorgensen and Stedman 2001: 234).

place dependence— "The strength of an individual's subjective attachment to specific places" (Stokols and Shumaker 1982: 157).

place identity—Dimensions of self that define an individual's [or group's] identity in relation to the physical environment through ideas, beliefs, preferences, feelings, values, goals, and behavioral tendencies and skills (Proshansky 1978).

place-based planning—"A process used to involve stakeholders by encouraging them to come together to collectively define place meanings and attachments" (Lowery and Morse 2013: 1423).

plant association—A fine level of classification in a hierarchy of potential vegetation that is defined in terms of a climax-dominant overstory tree species and typical understory herb or shrub species.

population bottleneck—An abrupt decline in the size of a population from an event, which often results in deleterious effects such as reduced genetic diversity and increased probability of local or global extirpation.

potential vegetation type (PVT)—Native, late-successional (or "climax") plant community that reflects the regional climate, and dominant plant species that would occur on a site in absence of disturbances (Pfister and Arno 1980).

poverty rate—A measure of financial income below a threshold that differs by family size and composition.

precautionary principle—A principle that if an action, policy, or decision has a suspected risk of causing harm to the public or to the environment, and there is no scientific consensus that it is not harmful, then the burden of proof that it is not harmful falls on those making that decision. Particular definitions of the principle differ, and some applications use the less formal term, "precautionary approach." Important qualifications associated with many definitions include (1) the perceived harm is likely to be serious, (2) some scientific analysis suggests a significant but uncertain potential for harm, and (3) applications of the principle emphasize generally constraining an activity to mitigate it rather than "resisting" it entirely (Doremus 2007).

prescribed fire—A wildland fire originating from a planned ignition to meet specific objectives identified in a written and approved prescribed fire plan for which National Environmental Policy Act requirements (where applicable) have been met prior to ignition (synonymous with controlled burn).

primary recreation activity—A single activity that caused a recreation visit to a national forest.

probable sale quantity—An estimate of the average amount of timber likely to be awarded for sale for a given area (such as the NWFP area) during a specified period.

provisioning services—A type of ecosystem service that includes clean air and fresh water, energy, food, fuel, forage, wood products or fiber, and minerals.

public participation geographic information system (PPGIS)—Using spatial decisionmaking and mapping tools to produce local knowledge with the goal of including and empowering marginalized populations (Brown and Reed 2009).

public values—Amenity values (scenery, quality of life); environmental quality (clean air, soil, and water); ecological values (biodiversity); public use values (outdoor recreation, education, subsistence use); and spiritual or religious values (cultural ties, tribal history).

record of decision (ROD)—The final decision document that amended the planning documents of 19 national forests and seven Bureau of Land Management districts within the range of the northern spotted owl (the NWFP area) in April 1994 (Espy and Babbit 1994).

recreation opportunity—An opportunity to participate in a specific recreation activity in a particular recreation setting to enjoy desired recreation experiences and other benefits that accrue. Recreation opportunities include non-motorized, motorized, developed, and dispersed recreation on land, water, and in the air (36 CFR 219.19).

redundancy—The presence of multiple occurrences of ecological conditions, including key ecological functions (functional redundancy), such that not all occurrences may be eliminated by a catastrophic event.

refugia—An area that remains less altered by climatic and environmental change (including disturbances such as wind and fire) affecting surrounding regions and that therefore forms a haven for relict fauna and flora.

regalia—Dress and special elements made from a variety of items, including various plant and animal materials, and worn for tribal dances and ceremonies.

regulating services—A type of ecosystem service that includes long-term storage of carbon; climate regulation; water filtration, purification, and storage; soil stabilization; flood and drought control; and disease regulation.

representativeness—The presence of a full array of ecosystem types and successional states, based on the physical environment and characteristic disturbance processes.

reserve—An area of land designated and managed for a special purpose, often to conserve or protect ecosystems, species, or other natural and cultural resources from particular human activities that are detrimental to achieving the goals of the area.

resilience—The capacity of a system to absorb disturbance and reorganize (or return to its previous organization) so as to still retain essentially the same function, structure, identity, and feedbacks (see FSM Chapter 2020 and see also “socioecological resilience”). Definitions emphasize the capacity of a system or its constituent entities to respond or regrow after mortality induced by a disturbance event, although broad definitions of resilience may also encompass “resistance” (see below), under which such mortality may be averted.

resistance—The capacity of a system or an entity to withstand a disturbance event without much change.

restoration economy—Diverse economic activities associated with the restoration of structure or function to terrestrial and aquatic ecosystems (Nielsen-Pincus and Moseley 2013).

restoration, ecological—The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed. Ecological restoration focuses on reestablishing the composition, structure, pattern, and ecological processes necessary to facilitate terrestrial and aquatic ecosystems sustainability, resilience, and health under current and future conditions (36 CFR 219.19).

restoration, functional—Restoration of dynamic abiotic and biotic processes in degraded ecosystems, without necessarily a focus on structural condition and composition.

riparian areas—Three-dimensional ecotones (the transition zone between two adjoining communities) of interaction that include terrestrial and aquatic ecosystems that extend down into the groundwater, up above the canopy, outward across the floodplain, up the near slopes that drain to the water, laterally into the terrestrial ecosystem, and along the water course at variable widths (36 CFR 219.19).

riparian management zone—Portions of a watershed in which riparian-dependent resources receive primary emphasis, and for which plans include Plan components to maintain or restore riparian functions and ecological functions (36 CFR 219.19).

riparian reserves—Reserves established along streams and rivers to protect riparian ecological functions and processes necessary to create and maintain habitat for aquatic and riparian-dependent organisms over time and ensure connectivity within and between watersheds. The Aquatic Conservation Strategy in the NWFP record of decision included standards and guidelines that delineated riparian reserves.

risk—A combination of the probability that a negative outcome will occur and the severity of the subsequent negative consequences (36 CFR 219.19).

rural restructuring—Changes in demographic and economic conditions owing to declines in natural resource production and agriculture (Nelson 2001).

scale—In ecological terms, the extent and resolution in spatial and temporal terms of a phenomenon or analysis, which differs from the definition in cartography regarding the ratio of map distance to Earth surface distance (Jenerette and Wu 2000).

scenic character—A combination of the physical, biological, and cultural images that gives an area its scenic identity and contributes to its sense of place. Scenic character provides a frame of reference from which to determine scenic attractiveness and to measure scenic integrity (36 CFR 219.19).

science synthesis—A narrative review of scientific information from a defined pool of sources that compiles and integrates and interprets findings and describes uncertainty, including the boundaries of what is known and what is not known.

sense of place—The collection of meanings, beliefs, symbols, values, and feelings that individuals or groups associate with a particular locality (Williams and Stewart 1998).

sensitive species—Plant or animal species that receive special conservation attention because of threats to their populations or habitats, but which do not have special status as listed or candidates for listing under the Endangered Species Act.

sensitivity—In ecological contexts, the propensity of communities or populations to change when subject to disturbance, or the opposite of resistance (see "community resistance").

sink population—A population in which reproductive rates are lower than mortality rates but that is maintained by immigration of individuals from outside of that population (see also "source population").

social sustainability—"The capability of society to support the network of relationships, traditions, culture, and activities that connect people to the land and to one another, and support vibrant communities" (36 CFR 219.19). The term is commonly invoked as one of the three parts of a "triple-bottom line" alongside environmental and economic considerations. The concept is an umbrella term for various topics such as quality of life, security, social capital, rights, sense of place, environmental justice, and community resilience, among others discussed in this synthesis.

socioecological resilience—The capacity of socioecological systems (see "socioecological system") to cope with, adapt to, and influence change; to persist and develop in the face of change; and to innovate and transform into new, more desirable configurations in response to disturbance.

socioecological system (or social-ecological system)—A coherent system of biophysical and social factors defined at several spatial, temporal, and organizational scales that regularly interact, continuously adapt, and regulate critical natural, socioeconomic, and cultural resources (Redman et al. 2004); also described as a coupled-human and natural system (Liu et al. 2007).

source population—A population in which reproductive rates exceed those of mortality rates so that the population has the capacity to increase in size. The term is also often used to denote when such a population contributes emigrants (dispersing individuals) that move outside the population, particularly when feeding a sink population.

special forest products—See "nontimber forest products."

special status species—Species that have been listed or proposed for listing as threatened or endangered under the Endangered Species Act.

species of conservation concern—A species, other than federally recognized as a threatened, endangered, proposed, or candidate species, that is known to occur in the NWFP area and for which the regional forester has determined that the best available scientific information indicates substantial concern about the species' capability to persist over the long term in the Plan area (36 CFR 219.9(c)).

stand—A descriptor of a land management unit consisting of a contiguous group of trees sufficiently uniform in age-class distribution, composition, and structure, and growing on a site of sufficiently uniform quality, to be a distinguishable unit.

standard—A mandatory constraint on project and activity decisionmaking, established to help achieve or maintain the desired condition or conditions, to avoid or mitigate undesirable effects, or to meet applicable legal requirements.

stationarity—In statistics, a process that, while randomly determined, is not experiencing a change in the probability of outcomes.

stewardship contract—A contract designed to achieve land management goals while meeting local and rural community needs, including contributing to the sustainability of rural communities and providing a continuing source of local income and employment.

strategic surveys—One type of field survey, specified under the NWFP, designed to fill key information gaps on species distributions and ecologies by which to determine if species should be included under the Plan's Survey and Manage species list.

stressors—Factors that may directly or indirectly degrade or impair ecosystem composition, structure, or ecological process in a manner that may impair its ecological integrity, such as an invasive species, loss of connectivity, or the disruption of a natural disturbance regime (36 CFR 219.19).

structure (ecosystem)—The organization and physical arrangement of biological elements such as snags and down woody debris, vertical and horizontal distribution of vegetation, stream habitat complexity, landscape pattern, and connectivity (FSM 2020).

supporting services—A type of ecosystem service that includes pollination, seed dispersal, soil formation, and nutrient cycling.

Survey and Manage program—A formal part of the NWFP that established protocols for conducting various types of species surveys, identified old-forest-associated species warranting additional consideration for monitoring and protection (see "Survey and Manage species"), and instituted an annual species review procedure that evaluated new scientific and monitoring information on species for potentially recommending changes in their conservation status, including potential removal from the Survey and Manage species list.

Survey and Manage species—A list of species, compiled under the Survey and Manage program of the NWFP, that were deemed to warrant particular attention for monitoring and protection beyond the guidelines for establishing late-successional forest reserves.

sustainability—The capability to meet the needs of the present generation without compromising the ability of future generations to meet their needs (36 CFR 219.19).

sustainable recreation—The set of recreation settings and opportunities in the National Forest System that is ecologically, economically, and socially sustainable for present and future generations (36 CFR 219.19).

sympatric—Two species or populations that share a common geographic range and coexist.

threatened species—Any species that the Secretary of the Interior or the Secretary of Commerce has determined is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range. Threatened species are listed at 50 CFR sections 17.11, 17.12, and 223.102.

timber harvest—The removal of trees for wood fiber use and other multiple-use purposes (36 CFR 219.19).

timber production—The purposeful growing, tending, harvesting, and regeneration of regulated crops of trees to be cut into logs, bolts, or other round sections for industrial or consumer use (36 CFR 219.19).

topo-edaphic—Related to or caused by particular soil conditions, as of texture or drainage, rather than by physiographic or climatic factors within a defined region or area.

traditional ecological knowledge—"A cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (Berkes et al. 2000: 1252). See also "native knowledge."

trailing edge—When describing the range of a species, the boundary at which the species' population is geographically contracting through local extinction at occupied sites.

trophic cascade—Changes in the relative populations of producers, herbivores, and carnivores following the addition or removal of top predators and the resulting disruption of the food web.

uncertainty—Amount or degree of confidence as a result of imperfect or incomplete information.

understory—Vegetation growing below the tree canopy in a forest, including shrubs and herbs that grow on the forest floor.

use of wildland fire—Management of either wildfire or prescribed fire to meet resource objectives specified in land or resource management plans (see "Managing wildfire for resource objectives" and "Prescribed fire").

variable-density thinning—The method of thinning some areas within a stand to a different density (including leaving dense, unthinned areas) than other parts of the stand, which is typically done to promote ecological diversity in a relatively uniform stand.

vegetation series (plant community)—The highest level of the fine-scale component (plant associations) of potential vegetation hierarchy based on the dominant plant species that would occur in late-successional conditions in the absence of disturbance.

vegetation type—A general term for a combination or community of plants (including grasses, forbs, shrubs, or trees), typically applied to existing vegetation rather than potential vegetation.

viable population—A group of breeding individuals of a species capable of perpetuating itself over a given time scale.

vital rates—Statistics describing population dynamics such as reproduction, mortality, survival, and recruitment.

watershed—A region or land area drained by a single stream, river, or drainage network; a drainage basin (36 CFR 219.19).

watershed analysis—An analytical process that characterizes watersheds and identifies potential actions for addressing problems and concerns, along with possible management options. It assembles information necessary to determine the ecological characteristics and behavior of the watershed and to develop options to guide management in the watershed, including adjusting riparian reserve boundaries.

watershed condition assessment—A national approach used by the U.S. Forest Service to evaluate condition of hydrologic units based on 12 indicators, each composed of various attributes (USDA FS 2011).

watershed condition—The state of a watershed based on physical and biogeochemical characteristics and processes (36 CFR 219.19).

watershed restoration—Restoration activities that focus on restoring the key ecological processes required to create and maintain favorable environmental conditions for aquatic and riparian-dependent organisms.

well-being—The condition of an individual or group in social, economic, psychological, spiritual, or medical terms.

wilderness—Any area of land designated by Congress as part of the National Wilderness Preservation System that was established by the Wilderness Act of 1964 (16 U.S.C. 1131–1136) (36 CFR 219.19).

wildlife—Undomesticated animal species, including amphibians, reptiles, birds, mammals, fish, and invertebrates or even all biota, that live wild in an area without being introduced by humans.

wildfire—Unplanned ignition of a wildland fire (such as a fire caused by lightning, volcanoes, unauthorized and accidental human-caused fires), and escaped prescribed fires.

wildland-urban interface (WUI)—The line, area, or zone where structures and other human development meet or intermingle with undeveloped wildland or vegetation fuels.

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