NORTHWEST FOREST PLAN
THE FIRST TEN YEARS (1994–2003)

Status and Trends of Populations and Nesting Habitat for the Marbled Murrelet

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Cover Photo

Marbled murrelet single egg laid on large moss-covered branch (platform), Olympic Mountains, Washington. Photo by Nick Hatch. Murrelet on nest (insert) photo by Tom Hamer.

Northwest Forest Plan—The First 10 Years (1994-2003): Status and Trends of Populations and Nesting Habitat for the Marbled Murrelet

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Abstract

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The Northwest Forest Plan (the Plan) is a large-scale ecosystem management plan for federal land in the Pacific Northwest. Marbled murrelet (*Brachyramphus marmoratus*) populations and habitat were monitored to evaluate effectiveness of the Plan. The chapters in this volume summarize information on marbled murrelet ecology and present the monitoring results for marbled murrelets over the first 10 years of the Plan, 1994 to 2003. The marbled murrelet was federally listed in 1992 as threatened in Washington, Oregon, and California. The Plan identified the marbled murrelet as a major objective in the Plan design and hence the status of the murrelet is a key indicator of the Plan's potential success. Effectiveness monitoring for the marbled murrelet has two facets: (1) assess population trends at sea by using a unified sampling design and standardized survey methods, and (2) establish a credible estimate of baseline nesting-habitat data by modeling habitat relations, and use the baseline to track habitat changes over time. Our primary monitoring objective was to determine the status and trends of marbled murrelet populations and nesting habitat in the Plan area.

To estimate marbled murrelet population size, we sampled from boats by using line transects within 8 km of the Washington, Oregon, and northern California coastline, covering about 3,400 mi^2. From 2000 to 2003, the largest population estimate was in Puget Sound and Strait of Juan de Fuca of Washington; the highest densities were along the coast of Oregon and California north of the Humboldt-Mendocino County line, and the smallest population and lowest density were from the Humboldt-Mendocino County line south about 200 mi to San Francisco Bay, California. Marbled murrelet population estimates did not change significantly over 4 years. We estimated that 15 or 9 total years of surveys will be needed to detect a 2 or 5 percent annual decrease, respectively, using a test threshold at 95 percent power. We used three modeling approaches to estimate the amount and distribution of baseline nesting habitat: expert judgment, ecological niche factor analysis, and logistic regression. Our logistic regression model predicted that murrelet nesting habitat is more likely at sites that are closer to the sea, are on relatively flat terrain, are topographically cooler, have relatively fewer conifers larger than pole size (≥10 in diameter at breast height [d.b.h.]), have greater basal area of trees larger than pole size, and have greater basal area of larger diameter trees (>30 in d.b.h.). Estimates of amounts of baseline nesting habitat differed with modeling approaches, but all models showed that over 80 percent of baseline habitat on federally administered land occurred in reserved lands. A high proportion of baseline habitat occurred on nonfederal land; amounts of nonfederal habitat differed among provinces. Fire and harvest have led to losses of nesting habitat since the Plan was implemented, with higher rates of loss on nonfederal land. We estimated that only 13 percent of U.S. Forest Service and Bureau of Land Management land had an even chance or better of being suitable nesting habitat; meaning that, relative odds (odds ratios) were equal to or exceeded that of known occupied nesting habitat. We compare the efficacies of the different model approaches, discuss implications of our results for future monitoring, and propose that a comprehensive evaluation of the potential breeding range of marbled murrelet be done for federal land in the Plan area.

Keywords: Marbled murrelet, monitoring, population, trends, habitat modeling, nesting habitat, Northwest Forest Plan.

Preface

This report is one of a set of reports produced on this 10-year anniversary of the Northwest Forest Plan (the Plan). The collection of reports attempts to answer questions about the effectiveness of the Plan based on new monitoring and research results. The set includes a series of status and trends reports, a synthesis of all regional monitoring and research results, a report on interagency information management, and a summary report.

The status and trends reports focus on establishing baselines of information from 1994, when the Plan was approved, and reporting change over the 10-year period. The status and trends series includes reports on late-successional and old-growth forests, northern spotted owl population and habitat, marbled murrelet population and habitat, watershed condition, government-to-government tribal relationships, socioeconomic conditions, and monitoring of project implementation under the Plan standards and guidelines.

The synthesis report addresses questions about the effectiveness of the Plan by using the status and trends results and new research. It focuses on the validity of the Plan assumptions, differences between expectations and what actually happened, the certainty of the findings, and, finally, considerations for the future. The synthesis report is organized in two parts: Part I–introduction, context, synthesis, and summary–and Part II-socioeconomic implications, older forests, species conservation, the aquatic conservation strategy, and adaptive management and monitoring.

The report on interagency information management identifies issues and recommends solutions for resolving data and mapping problems encountered during the preparation of the set of monitoring reports. Information management issues inevitably surface during analyses that require data from multiple agencies covering large geographic areas. The goal of this set of reports is to improve the integration and acquisition of interagency data for the next comprehensive report.

Executive Summary

Summary Information

Our report contains three types of summaries: abstract, technical, and executive. An "informative" abstract follows the main title page and each of the chapter title pages in this report. We end the report with a "technical" summary. The abstracts and technical summary restate the objectives, methods, and significant results for a technical audience. The "Executive Summary" focuses on the key findings with important implications to management in a nontechnical approach. Our primary monitoring objective was to determine the status and trends of marbled murrelet populations and nesting habitat in the Plan area.

Population Status and Trend

Major Findings

- We reported the first Planwide population estimates that used consistent and standard statistical survey methods for the marbled murrelet, which were developed and implemented through the Plan Effectiveness Monitoring Program.
- We estimated that the population size of marbled murrelets at sea was about 22,000 birds (on any single day) for the coastal waters adjacent to the Plan.
- The 95 percent confidence interval for the population size ranges from about 18,500 to 29,000 birds.
- Four years of surveying marbled murrelets was an insufficient sample to conclude that marbled murrelet populations changed significantly.
- We estimated that 6 years of at-sea surveys are needed to detect a 10 percent annual population decline in the coastal water adjacent to the Plan, and 9 years for a 5 percent and 15 years for a 2 percent change—with high certainty.
- We observed the highest densities of murrelets along the Oregon and northernmost California coasts and lowest along the California coast from the Humboldt-Mendocino County line to just south of San Francisco Bay.
- Among five study areas, the highest population of murrelets was observed in the Puget Sound and Strait of Juan de Fuca of Washington.

Implications

- What does a population value of about 22,000 marbled murrelets adjacent to the Plan mean?

The exact population size of marbled murrelets in North America is not known. Current population estimates based on at-sea surveys is about 950,000 birds (reviewed in chapter 2). Most of these birds occur in Alaska (about 860,000) and British Columbia (55,000 to 78,000). Our estimate of about 22,000 marbled murrelets off the coast adjacent to the Plan area suggests that only a small fraction of the total population (maybe 2 to 3 percent) uses this portion of the range during the breeding season and that the at-sea population of marbled murrelets associated with the Plan area during the breeding season is considerably lower than in other portions of its range. Although there are multiple, plausible causes for this (see chapter 2), none are definitive.

- Is the marbled murrelet population associated with the Plan stable, increasing, or decreasing?

The monitoring information that we collected to address this question is inconclusive. After 4 years of surveys, our data suggest that statistically credible trends with the current level of survey effort will take another decade of surveys to detect a 2 percent annual population decline (with 95 percent certainty), or another 5 years to detect a 5 percent annual decline. Where marbled murrelets have been monitored for more than 15 years, data suggest that populations have declined (reviewed in chapter 2):

Habitat Status and Trend

Major Findings

- We provided the first estimates of the amount and distribution of marbled murrelet potential nesting habitat by using consistent baseline data in the Plan area. We consider these habitat estimates to be an improvement over previous ones.
- Our estimates of potential nesting habitat at the province scale differed from those previously described in the Plan: higher in Washington Western Cascades, Oregon Coast Range, and California Coast Range and lower in Olympic Peninsula, Oregon Klamath, and California Klamath.
- Our models predicted that murrelet nesting habitat is more likely at sites that are closer to the sea, are on relatively flat terrain, are topographically cooler, have relatively fewer conifers above pole size (≥10 in d.b.h.), have greater basal area of trees above pole size, and that have greater basal area of larger diameter trees (>30 in d.b.h.).
- All habitat models showed that over 80 percent of baseline potential nesting habitat on federally administered lands occurred in reserved lands.
- In reserved lands including national parks, Washington had the highest amount of high-quality habitat, 44 percent of the total; Oregon and California had 36 and 20 percent, respectively. On federal lands outside national parks, Oregon had the most high-quality habitat.
- The Olympic Peninsula province accounted for nearly 20 percent of the high-quality habitat on federally administered lands; this habitat was primarily in national parks.
- Across all lands in the Plan area, we estimated that about 52 percent (2.1 million acres) of higher quality potential nesting habitat occurred on nonfederal lands.

- Of the two marbled murrelet Inland Management zones in the Plan, the Zone farthest from the coast, Zone 2, accounted for <2 percent of the estimated high-quality habitat on federally administered lands.
- Our models indicate that only about 13 percent of U.S. Forest Service and Bureau of Land Management land are above moderate-quality habitat for nesting.
- Potential nesting habitat was lost to fire and harvest in the first 10 years of the Plan; the rate of habitat loss was higher on nonfederal lands.

Implications

- Is marbled murrelet potential nesting habitat being maintained and restored on federal lands throughout the Plan area?

Not much additional habitat was expected to have developed in just the first 10 years of the Plan. Knowledge is lacking on how long it takes for a given set of stand conditions to develop into suitable marbled murrelet nesting habitat and on the rate newly restored habitat might be colonized by marbled murrelets. Thus, it is not possible at this time to evaluate how well the Plan has functioned to restore marbled murrelet habitat. Although some nesting habitat was lost on federally administered lands during the first 10 years of the Plan—primarily owing to fire, the amount was relatively small and may have been compensated by the conversion of new nesting habitat through "natural succession." Assuming that potential nesting habitat is maintained if it occurs in federally administered reserved lands, then over 80 percent was maintained during the first 10 years. In the entire Plan area, however, we estimated that about 40 percent of the higher quality potential nesting habitat was not on federally administered lands.

- How do the new baseline estimates of potential nesting habitat in the Plan area affect maintaining and restoring habitat of the marbled murrelet?

The adaptive management process described in the Plan calls for evaluating new information and for making adjustments as needed to improve implementation of the Plan. New habitat information in this report includes (1) changes in the amount and distribution of potential nesting habitat at several geographic scales and among land use allocations and (2) changes in the way potential nesting habitat is classified from a simple scheme of suitable and unsuitable to a versatile one with a range of suitability classes and gradients. In addition, our data and models suggested that, in general, nesting habitat maintained and restored in marbled murrelet Inland Management Zone 2 has a low likelihood of being used for nesting. Potentially important nesting habitat for murrelets in Zone 2 may occur in localized areas; however, data were inadequate to address this.

Keys to improving survey data include (1) building a comprehensive murrelet location database from surveys done by various state and federal land management units, which never has been done in a collaborative and centralized manner for the Plan area; (2) mapping those survey locations; and (3) carrying out additional surveys prioritized to systematically fill gaps in existing information by geographic area and habitat conditions.

Contents

Chapter 1: Introduction to Effectiveness Monitoring of the Northwest Forest Plan for Marbled Murrelets

Mark H. Huff

Abstract

Huff, Mark H. 2005. Introduction to effectiveness monitoring of the Northwest Forest Plan for marbled murrelets. In: Huff, Mark H.; Raphael, Martin G.; Miller, Sherri L.; Nelson, S. Kim; Baldwin, Jim, tech. coords. 2006. Northwest Forest Plan—the first 10 years (1994-2003): status and trends of populations and nesting habitat for the marbled murrelet. Gen. Tech. Rep. PNW-GTR-650. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 1-8. Chapter 1.

The Northwest Forest Plan (the Plan) is a large-scale ecosystem management plan for federal land in the Pacific Northwest. As part of the Plan, monitoring is done to evaluate its effectiveness in achieving its objectives. This chapter introduces effectiveness monitoring of marbled murrelets (*Brachyramphus marmoratus*) to determine population and habitat status and trends, covering the first 10 years of the Plan. In this chapter, I present background information on the following topics: The Northwest Forest Plan, effectiveness monitoring, effectiveness monitoring of marbled murrelets, and the monitoring collaborators.

Introduction

In the early 1990s, controversy over harvest of old-growth forests led to sweeping changes in management of federal forests in western Washington, Oregon, and northwest California. These changes were prompted by a series of lawsuits in the late 1980s and early 1990s that effectively shut down federal timber harvest in the Pacific Northwest. In response, President Clinton convened a summit in Portland, Oregon, in 1993. At the summit, President Clinton issued a mandate for federal land management and regulatory agencies to work together to develop a plan to resolve the conflict. The President's guiding principles followed shortly after the summit in his *Forest Plan for a Sustainable Economy and Sustainable Environment* or otherwise known as the Northwest Forest Plan (Tuchman et al. 1996: 229).

Immediately after the summit, a team of scientists and technical experts were convened to conduct an assessment of options (FEMAT 1993). This assessment provided the scientific basis for the environmental impact statement and record of decision (ROD; USDA and USDI 1994b) to amend Forest Service and Bureau of Land Management planning documents within the range of the northern spotted owl (*Strix occidentalis caurina*).

The Plan is a large-scale ecosystem management plan for federal land in the Pacific Northwest. The basis for the Plan was established in 1993 by work groups of the Forest Ecosystem Management Assessment Team (FEMAT 1993). The team's specific objectives were to "identify management alternatives that attain the greatest economic and social contribution from the forests of the region and meet the requirements of the applicable laws and regulations… and base its work on the best technical and scientific information currently available." The team's milestone report, titled *Forest Ecosystem Management: An Ecological, Economic, and Social Assessment* (FEMAT 1993), fundamentally changed federal land management in the Pacific Northwest. In 1994, the U.S. Forest Service and Bureau of Land Management first issued a final supplemental environmental impact statement (FSEIS) largely based on the management options and land allocations from the FEMAT report (USDA and USDI 1994a: Vols. I and II). This was followed by the Plan, a two-part decision document that (1) identified the selection of Alternative 9: the *Record of Decision for Amendments to Forest Service and Bureau of Land Management Planning Documents Within the Range of the Northern Spotted Owl*, and (2) provided specific management direction in the attached *Standards and Guidelines for the Management of Habitat for Late-Successional and Old-Growth Forest Related Species Within the Range of the Northern Spotted Owl* (USDA and USDI 1994b).

Although the Plan had an integrated approach to conservation, it was divided into three main components: terrestrial, aquatic, and social (USDA and USDI 1994b). Broad conservation objectives were established for each component, respectively, (1) to protect and enhance habitat for late-successional and old-growth forest related species; (2) restore and maintain the ecological integrity of watersheds and aquatic ecosystems; and (3) provide a predictable sustainable commodity resource production, maximizing the social economic benefits and assist long-term economic development and diversification. The success of the Plan hinges on implementing monitoring programs to detect changes in ecological and social systems, which are tiered to these conservation objectives, and on adaptive management processes that evaluate and use monitoring information to adjust conservation and management practices.

The Plan affects about 24.4 million acres of federally managed forests in 18 national forests and 7 Bureau of Land Management districts in northwestern California, western Oregon, and western Washington (fig. 1-1) in 12 physiographic provinces (fig. 1-2). To facilitate implementation of the Plan, the federal land base was separated into land allocations: late-successional reserves, congressionally reserved areas, administratively withdrawn areas, managed late-successional areas, riparian reserves, adaptive management areas, and matrix—federal land outside the previous six designations (fig. 1-3) (USDA and USDI 1994b). Each land allocation has specific management objectives and requirements described in the standards and guidelines, which must be adhered to while implementing the Plan.

Effectiveness Monitoring

Monitoring is the repeated process of collecting and evaluating information. For the Plan, procedures, conservation objectives, and results are being monitored to determine if implementation and accomplishments are as intended. Three types of monitoring were proposed by the Plan: implementation, effectiveness, and validation (USDA and USDI 1994b). Implementation monitoring verifies if Plan standards and guidelines were followed. Effectiveness monitoring examines the extent to which topics of interest (e.g., strategy or initiative) have achieved intended objectives by evaluating the observed outcomes or impacts against expectations. Validation monitoring examines if cause-and-effect relationships exist between management practices and environmental indicators.

A framework to evaluate the success of the Plan through monitoring is described in Mulder et al. (1999). Effectiveness monitoring is expected to determine the status and trends of resources at multiple scales so that Planwide evaluations can be made (Mulder and Palmer 1999). Monitoring resource "status" entails examining the conditions of an indicator resource at a given moment in time, while "trends" involves following the resource change over time. Trend information can provide insights into the causes and consequences of changes, and help decisionmakers determine if and how management practices should be altered (Noon et al. 1999).

Effectiveness Monitoring of the Marbled Murrelet

The marbled murrelet (*Brachyramphus marmoratus*) was federally listed in 1992 as threatened in Washington, Oregon, and California (USFWS 1992). Within this range, a recovery plan, subdivided into six Conservation Zones was developed by the U.S. Fish and Wildlife Service in 1997 (USFWS 1997) (fig. 1-4). The Plan, which overlaps Conservation Zones 1 through 5 (fig. 1-4), identifies specific objectives and standards and guidelines to provide for persistence of this species, including surveys prior to ground-disturbing activities (USDA and USDI 1994b). The

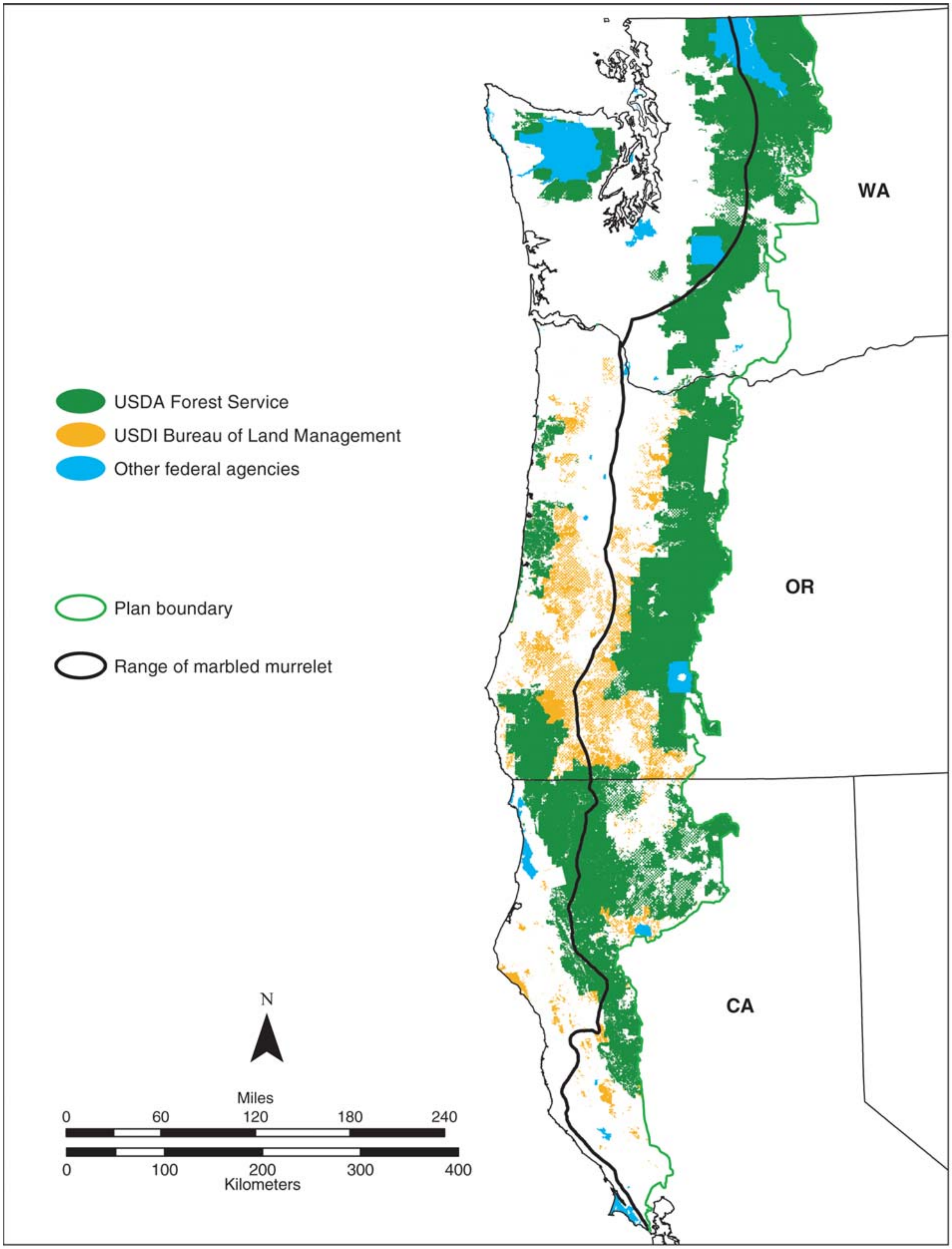

Figure 1-1—U.S. Forest Service and Bureau of Land Management administrative units in the Northwest Forest Plan area.

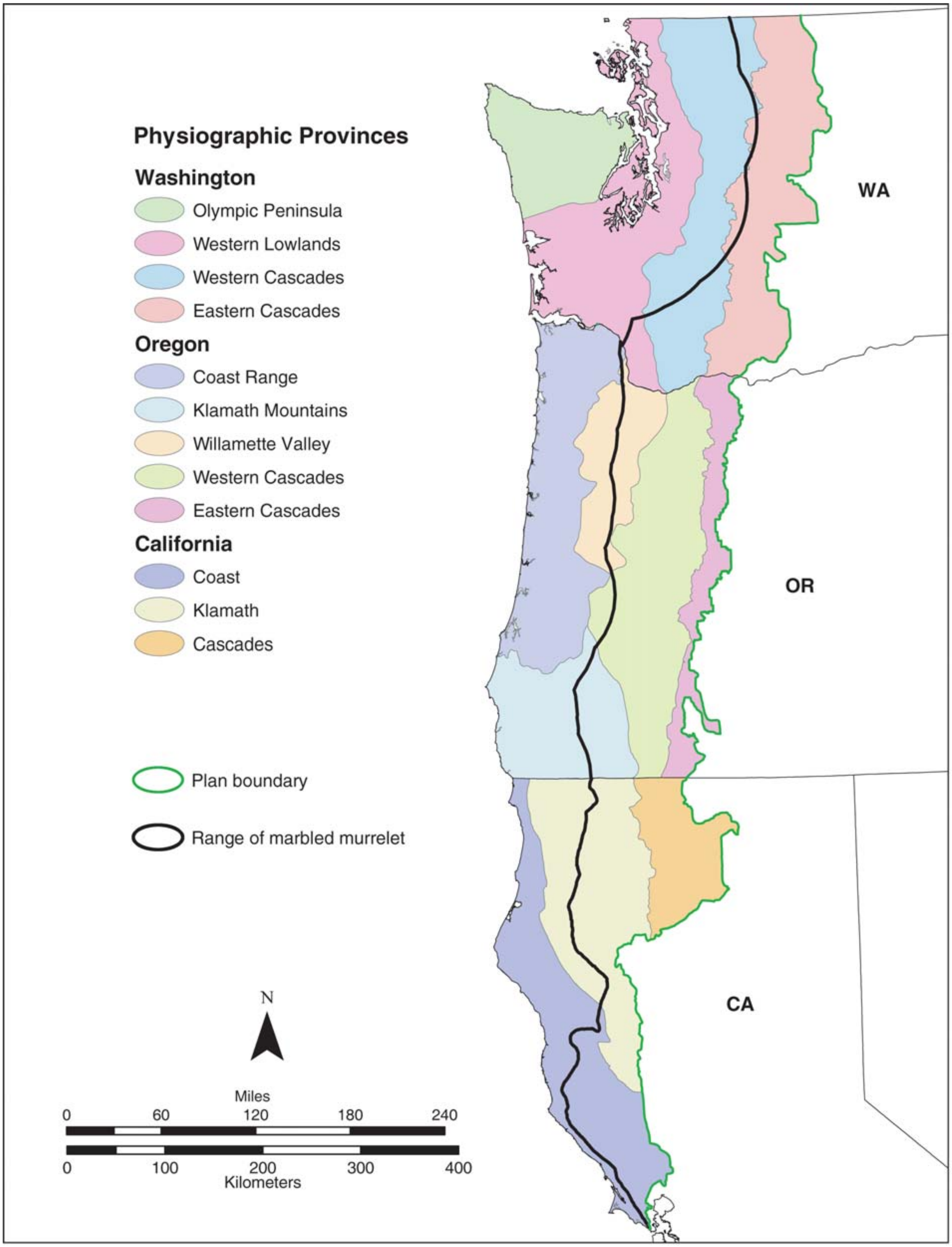

Figure 1-2—Physiographic province boundaries as defined by the Forest Ecosystem Management Assessment Team in the Northwest Forest Plan (Plan) area (1993).

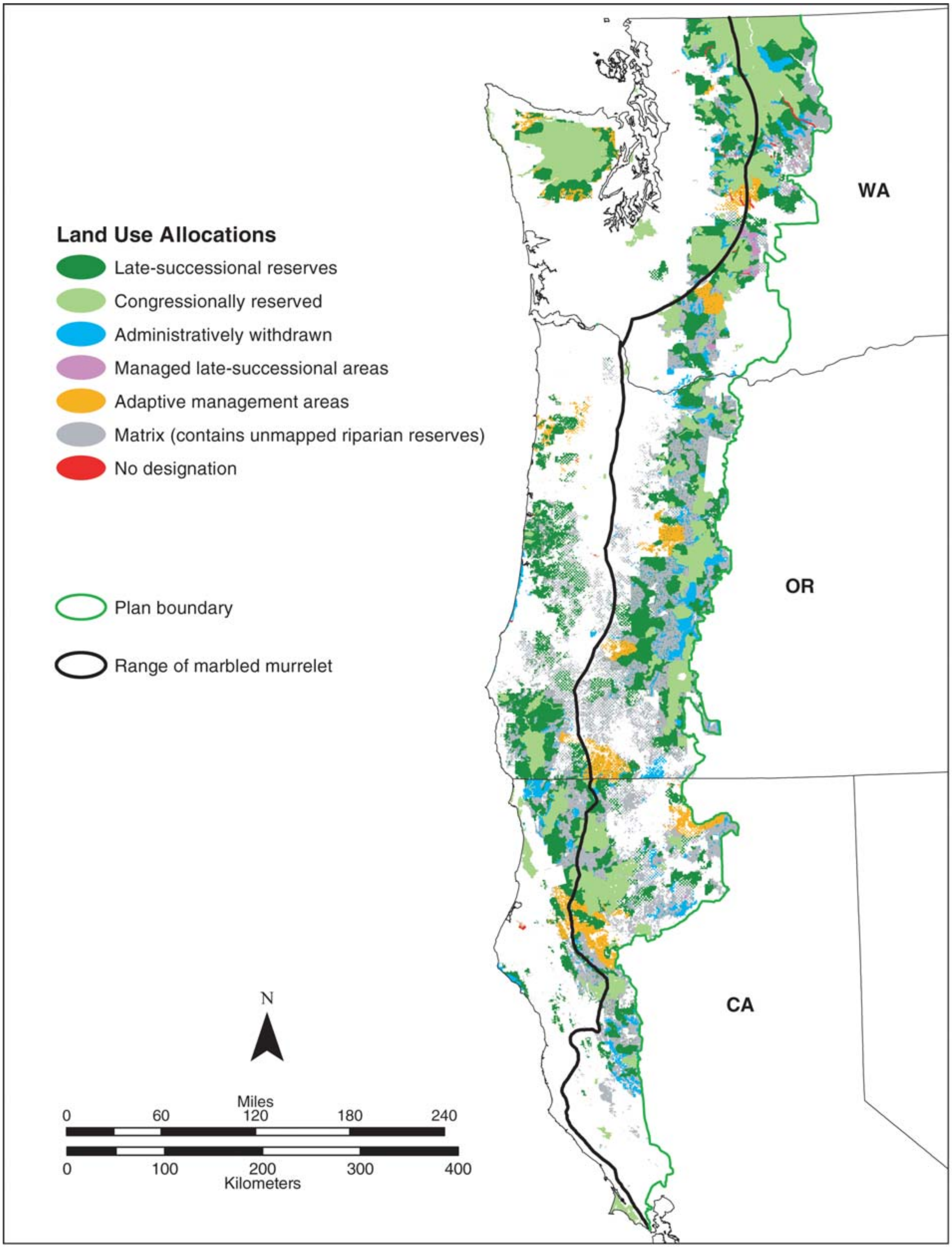

Figure 1-3—Land use allocations designated in the Northwest Forest Plan (Plan).

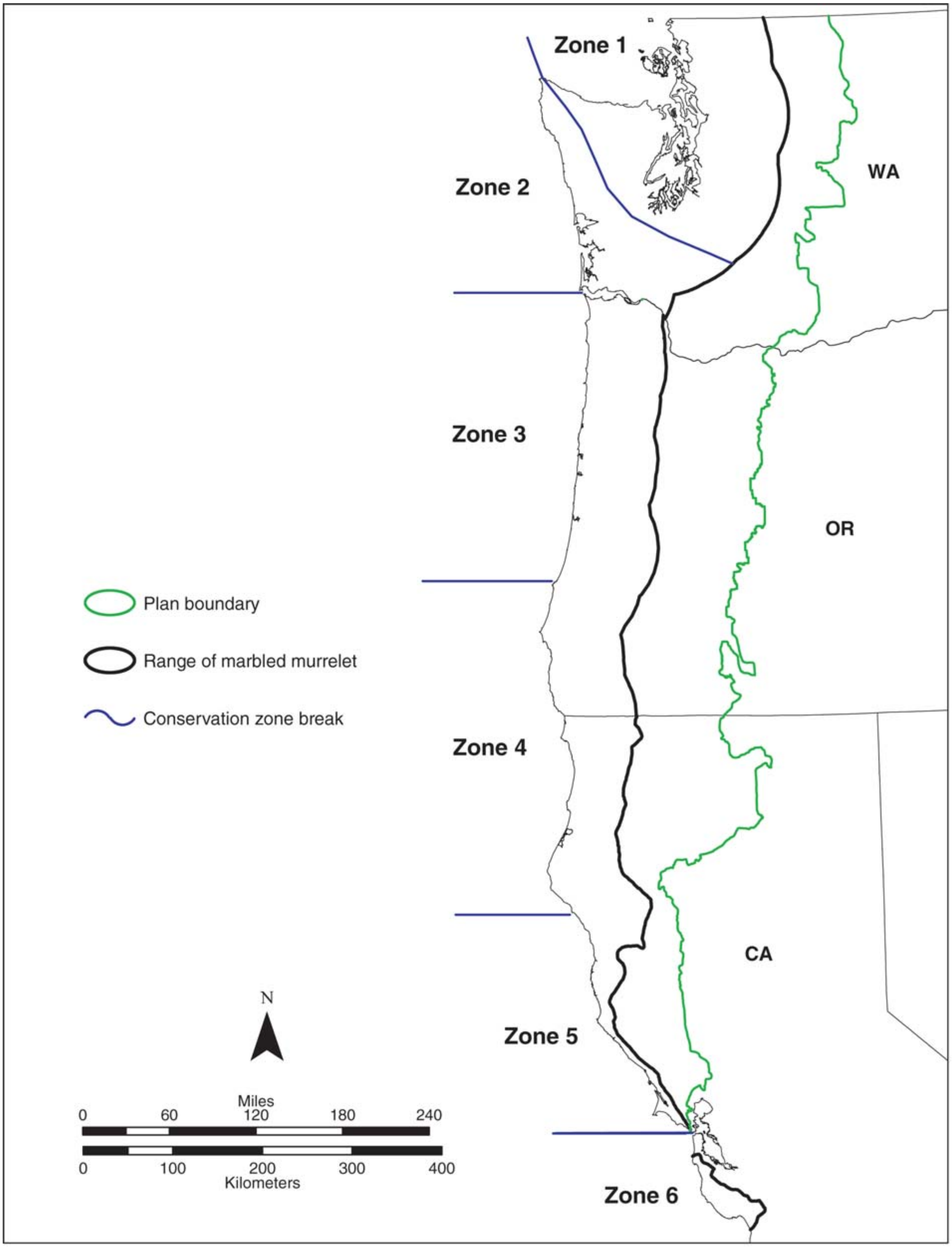

Figure 1-4—The six geographic areas identified as marbled murrelet Conservation Zones in the recovery plan for this species (USFWS 1997).

charter for FEMAT specifically directed the agencies to provide habitat condi-tions to support viable populations of the northern spotted owl and marbled murrelet (FEMAT 1993). Because a con-servation objective of the Plan was to support stable and well-distributed populations of these two species, they are key indicators of the Plan's potential success. Thus, these species were selected for effectiveness monitoring. In addition to specific monitoring of these two species, four other key components were selected to monitor Plan effectiveness: late-successional and old-growth forest, aquatic and riparian ecosystems, social and economic indicators, and tribal rights and interests.

In 1999, Madsen et al. described an effectiveness monitoring approach for the marbled murrelet under the Plan with two facets: population and habitat monitoring. The approach recommends assessing population trends at sea by using a unified sampling design and standardized survey methods. For habitat monitoring, the approach recommends establishing a credible baseline of nesting-habitat data by modeling habitat relations, and then by using the baseline to track habitat changes over time. The steps outlined in these approaches were followed where sufficient budgets were provided. The initial investments of nearly $1.6 million proposed in Madsen et al. (1999: table 5) to refine habitat definitions and identify key habitat variables and $1.1 million to validate habitat maps, for the most part, did not materialize. Assessments of population productivity (i.e., postbreeding surveys of juvenile-to-adult ratios) were not funded at levels to provide reliable planwide information over time and thus were dropped from the monitoring program.

This volume describes the results of monitoring marbled murrelets for the first 10 years of the Northwest Forest Plan. The purpose of the first two chapters is to provide context and background information to support subsequent chapters (chapters 3 through 5) that present monitoring results. Chapter 2 is a literature review of pertinent ecological information on marbled murrelets. Population status and trend results from 2000 to 2003[1] are presented in chapter 3. The next two chapters examine nesting habitat status and trends by using different modeling approaches. For estimating amounts of suitable nesting habitat, chapter 4 investigates using ground-based vegetation inventories remeasured at regular intervals, and chapter 5 investigates uses of interpreted satellite imagery. The report concludes with a "Summary" in chapter 6. A synthesis on Plan monitoring of marbled murrelets was developed in a companion publication (Raphael et al., in press).

Collaborators

In 1998, the U.S. Fish and Wildlife Service convened two teams and provided a single lead for these teams in order to design and implement status and trend monitoring of marbled murrelet populations and nesting habitat. Since then, there have been three U.S. Fish and Wildlife leaders for the marbled murrelet monitoring module: Naomi Bentivoglio (prior to June 2001), Patrick Jodice (October 2001 through September 2002), and Mark Huff (February 2003 to the present). Members of the population team have included Jim Baldwin, Sherri Miller, and C.J. Ralph, USDA Forest Service, Pacific Southwest Research Station; Tim Max and Martin Raphael, USDA Forest Service, Pacific Northwest Research Station; Gary Falxa and Ken Ostrom, U.S. Fish and Wildlife Service; Craig Strong, Crescent Coastal Research; Steven Beissinger, University of California Berkeley (prior to 2001); and Chris Thompson, Washington Department of Fish and Wildlife. Members of the nesting habitat team have included Jim Baldwin and Sherri Miller, USDA Forest Service, Pacific Southwest Research Station; Tom Bloxton, Diane Evans-Mack, Tim Max, Martin Raphael, and Randall Wilk, USDA Forest Service, Pacific Northwest Research Station; Kim Nelson, Oregon State University; and Ken Ostrom and Rich Young, U.S. Fish and Wildlife Service.

[1] The first year of our at-sea population surveys was 2000, which sampled marbled murrelets in the coastal waters adjacent to the Plan area using a standardized design.

Metric Equivalents

acres x 0.405 = hectares

Acknowledgments

This chapter was improved by review comments from Martin Raphael, Sherri Miller, Kim Nelson, Bruce Bingham, Rowan Baker, and Craig Palmer.

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Chapter 2: Marbled Murrelet Biology: Habitat Relations and Populations

S. Kim Nelson, Mark H. Huff, Sherri L. Miller, and Martin G. Raphael

Abstract

Nelson, S. Kim; Huff, Mark H.; Miller, Sherri L.; Raphael, Martin G. 2006. Marbled murrelet biology: habitat relations and populations. In: Huff, Mark H.; Raphael, M.G.; Miller, S.L.; Nelson, S.K.; Baldwin, J. tech. coords. Northwest Forest Plan—The first 10 years (1994-2003): status and trends of populations and nesting habitat for the marbled murrelet. Gen. Tech. Rep. PNW-GTR-650. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 9-30. Chapter 2.

This chapter summarizes information on the natural history, behavior, habitat associations, and population status and trends of the marbled murrelet (*Brachyramphus marmoratus*). Marbled murrelets are noncolonial, secretive alcids that occur along the Pacific coast of North America. In the southern portion of their range, they are generally nonmigratory, remain near nesting areas year round, and forage in pairs or small groups for schooling fish or invertebrates in sheltered waters generally within 3 mi of shore. Murrelets primarily nest in trees in coastal older aged coniferous forests within 52 mi of the ocean. Their breeding season lasts up to 182 days (between April and September) and is highly asynchronous. They do not build a nest, but lay their single egg on platforms created by large or deformed tree branches. Key components of their nesting habitat at the tree and stand scales include large platforms with substrate (generally moss) and foliage cover above the nest, high densities of large trees, numerous canopy layers, and naturally occurring canopy gaps to allow access to nest sites. At the landscape scale, murrelet nesting and occupied detections have generally been associated with unfragmented watersheds, large patch size, and minimal edge. Current population estimates based on at-sea surveys are as high as 950,000 birds. Major population declines (22 to 73 percent) over a decade or more have been documented in British Columbia and Oregon, and suggested in specific areas in Alaska. Because of a variety of disturbances in their marine and forested environments, marbled murrelets are listed as threatened in British Columbia, Washington, Oregon, and California.

Introduction

The marbled murrelet (*Brachyramphus marmoratus*) is a small, fast-flying seabird in the alcid family that occurs along the Pacific coast of North America. Murrelets forage for small schooling fish or invertebrates in shallow marine waters near shore and primarily nest in coastal older aged coniferous forests within 52 mi of the ocean. Populations of this species are thought to be in decline primarily because of nesting habitat loss; 50 to 90 percent of older aged forest habitat in the Pacific Northwest has been lost because of logging and development, and much of what remains is highly fragmented (Alig et al. 2000, Bolsinger and Waddell 1993, Garman et al. 1999, Hansen et al. 1991, Wimberly and Spies 2000). Other factors such as mortality in gill nets and oil spills, and high predation rates at nest sites have also affected population viability (Carter and Kuletz 1995, Carter et al. 1995, Nelson and Hamer 1995, Raphael et al. 2002b). The murrelet was listed as a federally threatened species in Washington, Oregon, and California in 1992 (USFWS 1997) and British Columbia in 1990 (Rodway 1990).

Subsequent to its listing, the Northwest Forest Plan (hereafter, the Plan; FEMAT 1993; USDA and USDI 1994a, 1994b) was created to protect sensitive and listed species occurring in late-successional forests on federal lands in Washington, Oregon, and California. The Plan land base and operating guidelines were expected to make substantial contributions toward conservation and recovery of the marbled murrelet and its habitat over the long term, and specific monitoring requirements have been outlined to assess the degree to which this objective has been met. Mulder et al. (1999) developed an overall approach for monitoring the Plan from which Madsen et al. (1999) tailored a more specific murrelet effectiveness monitoring plan that outlined the research needs and methods for evaluating the success of the Plan in providing adequate habitat for restoring murrelet populations. The effectiveness monitoring plan recommended establishing a credible nesting habitat baseline and assessing populations at sea under a unified sampling design with standardized survey methods. The trends in nesting habitat and population abundance are expected to be tracked over time.

This chapter provides a review of the natural history, behavior, habitat associations, and population status and trends of the marbled murrelet based primarily on published literature. More detailed reviews of murrelet ecology can be found in Burger (2002a), McShane et al. (2004), Nelson (1997), and Ralph et al. (1995a). These papers were used as important information sources in developing our review of murrelet biology, habitat associations, and population status. We emphasized information from within the Plan area (Washington, Oregon, and California), although data from British Columbia and Alaska are included where pertinent.

Murrelet Biology

Distribution

During the breeding season, marbled murrelets are found in the near-shore, coastal waters (generally 0 to 3 miles; up to 25 mi in Alaska) from the Aleutian Islands in Alaska south to central California (Santa Cruz County). Their distribution within the listed range and the Plan area encompasses about 18 percent of the linear range of the species. This area includes approximately 2 to 3 percent of the overall population (see Miller et al., chapter 3 of this volume). Most of the population (>90 percent) occurs between south-central Alaska (Prince William Sound, Kodiak Archipelago) and southern British Columbia. Gaps in their distribution occur along the Aleutian Islands, southeast Vancouver Island, lower mainland British Columbia, southern Washington to northern Oregon, and northern California (especially between Humboldt and San Mateo Counties) (Lank et al. 2003, USFWS 1997). Significant differences in murrelet population genetic structure suggest five distinct population segments: (1) western Aleutian Islands, (2) central Aleutian Islands, (3) mainland Alaska and British Columbia, (4) northern California, and (5) southern California (Friesen et al. 2005).

In the nonbreeding season, small numbers of murrelets have been reported as far north as the Chukchi Sea and as far south as northern Baja California, Mexico. Birds generally disperse and are less concentrated in near-shore coastal waters during the nonbreeding season, especially in Alaska where they generally occur more than 25 mi (and sometimes >62 mi) offshore.

The inland distance marbled murrelets travel during the breeding season differs with habitat availability, energetics, predation pressure, and a variety of other factors (reviewed in McShane et al. 2004). Most birds appear to nest within 37 mi of the coast, although occupied behaviors have been recorded up to 52 mi inland in Washington (B. Ritchie[1]) and a grounded chick was found at 62 mi inland in British Columbia (Nelson 1997). Birds have been documented flying over the canopy 70 mi inland in Washington (see footnote 1). In the southern portion of their range, murrelets occur inland during all months of the year except during their 2-month prebasic fall molt when they are flightless (Naslund 1993, Nelson 1997).

Marbled murrelets are generally nonmigratory and remain near nesting areas year round in the southern portion of their range. In contrast, in Alaska and many areas of British Columbia, where birds do not regularly attend nesting sites in winter, significant southward movements can occur (Agler et al. 1998, Beauchamp et al. 1999, Burger 1995b). For example, murrelets in the Queen Charlotte Islands and along the outer coast of Vancouver Island, British Columbia, disperse southward during the postbreeding season to more sheltered, shallow waters along the mainland (Burger 1995b, Chatwin et al. 2000, Mason et al. 2002).

[1] Ritchie, B. 2004. Personal communication. Wildlife biologist, Washington Department of Fish and Wildlife, 600 N Capitol Way, Olympia, WA 98504.

Nesting Behavior and Chronology

Murrelets are generally seen in pairs year round, suggesting that pair-bonds are strong and persistent in more than one breeding season (McFarlane Tranquilla et al. 2003c). During the winter (January through February), marbled murrelets begin their courtship activities in the near-shore waters, often while still in basic plumage. Copulation has been observed on the water and on branches of large trees (Nelson 1997). Murrelets begin laying their single egg in late March, but some eggs are laid as late as July (McFarlane Tranquilla et al. 2003b; Hamer et al., n.d.[2]). Renesting after early failure has been documented at several nests in California and British Columbia (Hebert et al. 2003, McFarlane Tranquilla et al. 2003a). Chicks hatch between May and August after 30 days of incubation and remain on the nest for 27 to 40 days (Nelson 1997). The prolonged murrelet breeding season lasts up to 182 days and is highly asynchronous both seasonally and regionally (Lougheed et al. 2002, McFarlane Tranquilla et al. 2003b, 2005; Nelson 1997; and see footnote 2). The timing of breeding varies with latitude and is also likely affected by prey availability, ocean conditions, and other factors.

Unlike most other alcid species, marbled murrelets are solitary nesters. They nest individually on large limbs of coniferous trees or on the ground, although ground nesting is only known to occur in British Columbia and Alaska (Bradley and Cooke 2001, DeGange 1996). During incubation, one adult sits on the nest while the other forages at sea. Every 24 hours at dawn they exchange incubation duties. Chicks are semiprecocial (fully feathered) at hatching and may be brooded by one or both adults for several days. Once chicks attain thermoregulatory independence, both adults leave the chick alone on the nest to forage at sea (see Burkett 1995 for a list of prey species). The chick typically receives 1 to 8 meals per day (mean 3.2); most feedings are at dawn and dusk but some occur during midmorning (Nelson 1997). The number of visits by each adult differs seasonally, and males have been documented to make more feeding trips than females (1.3 times overall and 1.8 times at dusk; Bradley et al. 2002). Adults usually bring the chick a single whole fish and remain at the nest for brief periods (30 seconds to 80 minutes). After 27 to 40 days on the nest and at 58 to 71 percent of adult mass, chicks are thought to fly alone at dusk directly from the nest site to the ocean. Chicks do not appear to receive parental care at sea and generally forage solitarily. Groups of chicks, however, have been seen congregating in late summer in some areas of Alaska (e.g., Kuletz and Piatt 1999).

Murrelets fly inland to nesting sites in increasingly higher numbers as the breeding season approaches. Activity peaks in late June and early July and drops off quickly in early August. They are most active in the forest at dawn, when groups of birds circle and call loudly over or near nesting sites. The degree to which nesting birds participate in this circling and calling activity is unknown (see next paragraph). It is during this time that standardized surveys are conducted for determining murrelet site status (Evans-Mack et al. 2003). Results of these surveys are used to classify sites as occupied (birds flying through the canopy or circling the stand), present (birds flying over the canopy), or absent (no detections).

Murrelets exhibit specific behavioral patterns and morphological characteristics that are meant to minimize predation at nest sites (Nelson 1997, Nelson and Peck 1995). Nesting birds are generally secretive in proximity to nests sites, approaching directly, quietly, and generally below canopy during low light levels. Interactions between adults on the nest are brief and vocalizations are generally muted. The plumage of both the adults and chicks is also cryptic, and nestlings do not molt into their juvenal plumage until just before fledging. This combined with their rapid flight (at least 43 mi per hour; Burger 2002a), makes murrelet nests difficult to locate.

Individual murrelets are suspected to have fidelity to nest sites or nesting areas, although this has been verified with marked birds in only a few cases (Hebert and Golightly

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[2] Hamer, T.E., Nelson, S.K., Mohagen, T.I. [N.d.] Nesting chronology of the marbled murrelet in North America. Manuscript in preparation. On file with: T.E. Hamer, Hamer Environmental L.P., 19997 Highway 9, Mt. Vernon, WA 98274.

2003, R. Bradley[3]). Repeated surveys in occupied or nesting stands have revealed site tenacity similar to that of other birds in the alcid family (Evans-Mack et al. 2003, Gaston and Jones 1998, Nettleship and Birkhead 1985). The degree of philopatry, or the proportion of young that return to breed at their natal areas, is unknown. (For details on their demography see Burger 2002a and McShane et al. 2004).

Forest Habitat Associations

In the following discussions, only the habitat characteristics associated with tree nesting will be addressed. The nesting habitat preferences of murrelets have been evaluated at a variety of scales, including the tree, stand, and landscape scales. Research on murrelet nesting habitat began with an emphasis on the components of the nest tree (e.g., Quinlan and Hughes 1990). More recently, research has focused on stand- and landscape-level habitat associations (e.g., Burger and Chatwin 2002, Nelson et al. 2003, Waterhouse et al. 2002). Assessing habitat associations at all scales is necessary to fully understand the factors that limit populations. Below we review habitat associations at different scales that were derived either from murrelet nest sites or sites where occupancy was determined but a specific nest was not found.

Tree-Level Associations

The most important component of murrelet nesting habitat at the tree scale is the presence of large platforms (defined as limbs ≥10 cm [4 in] and ≥10 m [33 ft] in height; reviewed in Burger 2002a, McShane et al. 2004). The abundance of substrate, foliage cover above and around the nest, tree size, limb height, and location of the nest tree with respect to openings also are factors in determining suitability of nesting habitat. Murrelets do not build nests, but they lay their single egg on platforms created by large or deformed tree branches. Large limbs are important for providing a platform for nesting, and substrate on the tree limb (moss, needles, or duff) provides for a nest cup and to protect the egg from rolling off. Foliage cover above and around the nest provides protection from the weather and visually screens the nest from detection by predators. The platform needs to be at sufficient height to allow jumpoff departures and stall landings. Openings near nest sites (at the tree and stand scales) provide murrelets with flight space or access to their nest trees.

Tree diameter and height have been correlated with platform size and the abundance of platforms, but the relationship does not always occur given the variety of trees species and forest types murrelets use for nesting. For example, in the Sitka spruce/western hemlock forest type, murrelets can nest in young trees (60 to 80 years in age) because of platforms created by dwarf mistletoe (*Arceuthobium* spp.) infestations (Nelson and Wilson 2002).

Tree species—
Murrelets do not appear to favor particular tree species. They have nested in a variety (at least eight) of conifer tree species (Burger 2002a, Hamer and Nelson 1995, McShane et al. 2004). Only one nest has been found in a deciduous tree (red alder [*Alnus rubra*] Bong.) (Bradley and Cooke 2001). Generally, the nest tree species are dominant or fairly abundant within the forest types used for nesting. All the nest tree species can have large platforms when the trees are large or when deformities are present. Tree species can vary, however, in the abundance of platforms and other nest-tree characteristics. For example, Hamer (1995) found that Sitka spruce (*Picea sitchensis* (Bong.) Carr.) trees were larger, taller, and had more platforms and moss than other tree species in the forests of western Washington. But Hamer and Meekins (1999) suggested that western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) had the best combination of attributes for nesting. In addition, the probability of occupancy increased with the presence of large western hemlock trees (Hamer 1995). In south-central Alaska, Sitka spruce trees were thought to exhibit the best qualities for murrelet nesting when compared with other species (Naslund et al. 1995).

[3] Bradley, R. 2005. Personal communication. Seabird biologist, PRBO Conservation Science, Marine Science Division, 4990 Shoreline Hwy, Stinson Beach, CA 94970.

Tree size—

Nests have occurred primarily in large, tall old-growth trees. Overall, nest trees in the Plan area have been >48 cm (19 in) diameter at breast height (d.b.h.) and >30 m (98 ft) tall (Burger 2002a, Hamer and Nelson 1995, Nelson and Wilson 2002). The young and mature (66 to 150 years; n = 20) western hemlock and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees that Nelson and Wilson (2002) found in Oregon were generally large (>19 in d.b.h.; 85 percent ≥30 in d.b.h.) and tall (>110 ft), and had large platforms created by deformations or dwarf mistletoe infections.

Tree size has been identified as an important nest characteristic in several studies. Preliminary results showed that nest trees were taller than nonnest trees in western Washington (175 versus 161 ft), and nest trees were larger in diameter than trees that did not contain nests in western Washington and Oregon (Washington 43.4 versus 39.3 in; Oregon 47.3 versus 32.8 in) (Hamer and Meekins 1999, Nelson and Wilson 2002). In British Columbia and Alaska, trees containing nests were significantly larger in diameter than nonnest trees (Conroy et al. 2002, Manley et al. 1999, Naslund et al. 1995). In British Columbia, nest trees were also taller than nonnest trees (138 versus 115 ft), but the differences were not significant (Conroy et al. 2002).

Platforms and substrate—

The presence of platforms is the most important characteristic of murrelet habitat (reviewed in Burger 2002a, McShane et al. 2004, Nelson 1997). Because murrelets do not build a nest, large platforms are required for providing a place to lay their single, large egg. All nest platforms were ≥4 inches in diameter and ≥33 ft above the ground (as defined). Substrate on the nest limb is important for protecting the egg and preventing it from falling. The substrate found at most nests has been a variety of species of moss, although duff, needles, and sticks have also been recorded. The depth of the substrate has varied widely from 0.3 to 5.0 in, with a mean depth of 1.1 to 2.0 in (n = 61 nests).

In descriptive studies, nest trees generally had more platforms, larger platforms, and more moss than nonnest trees. Preliminary results from western Washington and Oregon indicated that nest platforms were larger in diameter (Washington mean 26.1 versus 19.1 in; Oregon mean 21.0 versus 17.2 in) and had deeper moss (Washington mean 1.7 versus 0.6 in) than random non-nest platforms (Hamer and Meekins 1999, Nelson and Wilson 2002). In addition, nest trees had more large platforms (>6 in) than nonnest trees (Washington mean 14.1 versus 5.7; Oregon mean 21.1 versus 4.6), with very large platforms (>8 in diameter) three times more abundant in nest trees versus nonnest trees in western Washington (Hamer and Meekins 1999). In Clayoquot Sound, British Columbia, trees containing nests had more platforms (mean 10 versus 7) and epiphyte cover (mean 72 versus 54 percent) than nonnest trees (Conroy et al. 2002). On the Sunshine Coast, British Columbia, nest platforms were larger in diameter and nest trees had more potential nesting platforms than random available platforms and trees, respectively (Manley et al. 1999). Perimeter forests (small, narrow strips) along the ocean on western Vancouver Island were low-quality habitat based on low densities of platforms and high predator numbers (Burger et al. 2000, Rodway and Regehr 2002). The highest quality habitat included productive, unfragmented, old-growth stands located away from the ocean and harvest edges, and in slope areas below 800 m (2,625 ft) in elevation.

Predictive studies also demonstrated murrelet preferences for nest trees with large limbs, numerous platforms, and high epiphyte levels. The number of platforms per tree was selected as the first variable or it explained the most variation in tree-level habitat models in studies in British Columbia, Washington, and Oregon (Hamer and Meekins 1999, Manley 1999, Nelson and Wilson 2002, Nelson et al. 2003). In Oregon, platform width, substrate depth, and percentage of moss were the best predictors of murrelet nest platforms. In addition, in Washington, the probability of occupancy increased with increasing number of potential platforms and percentage of moss cover on limbs of large trees (Hamer 1995). In Alaska, one of the best predictors for observing occupied behaviors was number of platforms (Kuletz et al. 1995).

Tree size is not always correlated with the occurrence of platforms; this relationship has differed with tree species (see above), site productivity, and stand moisture levels. For example, Nelson et al. (2003) found no correlation between the two variables, most likely related to murrelet use of younger trees with mistletoe platforms. In contrast, McLennan et al. (2000) found that stands with taller, larger trees included higher densities of potential nest platforms. Hamer (1995), Manley (1999), and Raphael (2004) also found a strong correlation between tree diameter and the number or probability of occurrence of platforms. Relationships varied among tree species, but generally trees greater than 35 in d.b.h. had a 50 percent or greater likelihood of having platforms.

Horizontal and vertical cover—

Nest platforms have generally been protected by branches above (vertical cover) or to the side (horizontal cover). The amount of vertical cover was generally greater than 70 percent (Hamer and Nelson 1995, Manley 1999). Nest platforms had higher vertical cover than nonnest or available platforms in Washington, Oregon, and British Columbia (Hamer and Meekins 1999, Manley et al. 1999, Nelson and Wilson 2002). Vertical cover was also an important predictor of murrelet nesting habitat in models developed at the platform scale in Oregon (Nelson and Wilson 2002, Nelson et al. 2003). Horizontal cover was not measured in all studies, but in Oregon and Washington, nest platforms had more horizontal cover than nonnest platforms (Hamer and Meekins 1999, Nelson and Wilson 2002). Murrelets appear to select limbs and platforms that provide them protection from predation (Luginbuhl et al. 2001, Marzluff et al. 2000, Raphael et al. 2002b) and inclement weather. Nest success, however, is influenced not only by cover but also by distance to openings, predator numbers, and distance to human disturbance (reviewed in McShane et al. 2004).

Stand-Level Associations

At the stand level, murrelets are known to prefer areas with high densities of large trees with an abundance of moss-covered platforms (more common in moist and productive areas; Chatwin et al. 2000, Hamer 1995, Manley et al. 1999, Nelson and Wilson 2002, Nelson et al. 2003). Based on dawn surveys, tree climbing, and radio telemetry, murrelet stand-level preferences were also found to include vertical complexity or number of canopy layers and naturally occurring canopy gaps to allow access to nest sites (Chatwin et al. 2000, Manley et al. 1999, Nelson and Wilson 2002, Nelson et al. 2003, Waterhouse et al. 2002). Occupied sites in Oregon occurred in older forests with high densities of large, tall, dominant trees and large hardwoods on gentle slopes and in areas with less canopy cover than random sites (Grenier and Nelson 1995). In northern California, murrelet detection levels were highest in stands with high densities of old-growth trees, a greater proportion of redwoods, along major drainages, and at lower elevations (Miller and Ralph 1995).

In British Columbia, Rodway and Regehr (2002) found that the number of occupied detections was correlated with density of trees with platforms, density of large trees, and mean d.b.h. of all trees. By using aerial photointerpretation, Waterhouse et al. (2002) found that murrelets in British Columbia preferred older aged forest stands (>140 years) with tall, large trees and complex vertical structure including canopy gaps and multiple layers for nesting. They suggested that vertical complexity allowed for the formation of higher quality microhabitats for nests including large platforms and abundant epiphyte cover.

Density of platforms and platform trees—

Densities of platforms and platform trees were the most predictive variables at the stand scale. In Oregon and Washington, platform density was the only variable in the top-ranked model of murrelet nests and nonnest sites (Nelson and Wilson 2002, Nelson et al. 2003), although competing models included number of canopy layers and distance to edge in addition to platform density (see below under “Access”). In British Columbia, hierarchical models indicated that density of trees with platforms and other large trees were the main predictors of the number of murrelet detections after controlling for weather, date, and size of opening at their survey stations (Rodway and

Regehr 2002). In addition, Manley et al. (1999) found higher densities of platform trees in nest patches compared with available habitat in the stand.

Tree size—
In British Columbia, murrelet detection frequencies and the number of occupied detections were associated with moist, low-elevation forests with large trees and well-developed epiphyte mosses (Bahn and Newsom 2002a, Burger 1995a). In addition, the number of occupied detections was correlated with tree diameter and height (among other variables), allowing for comparisons with forest cover classes and construction of habitat suitability models (Chatwin et al. 2000). In Alaska and California, one of the best predictors of observing occupied behaviors was tree diameter (Kuletz et al. 1995, Meyer et al. 2004b).

Access—
Murrelets have a reduced wing surface area relative to their body size for reducing drag and assisting them with pursuing prey underwater. As a consequence, they must fly at high speeds (43 to 74 mi per hour) with rapid wing beats to maintain lift (Burger 2002a, Pennycuick 1987). Canopy gaps are therefore important for nest access. At their high flight speeds murrelets approach the nest tree (in an opening) from below in order to stall and land on the nest branch. They also need openings adjacent to their nest for jumpoff departures.

In research throughout their range, marbled murrelets were shown to prefer nest trees adjacent to canopy gaps, including river corridors, forest gaps, and forest edges (Bradley 2002, Hamer and Meekins 1999, Manley et al. 1999, Naslund et al. 1995, Nelson and Wilson 2002, Singer et al. 1991). Murrelets have also nested in areas with numerous canopy layers, high canopy closure, or in areas with high densities of large trees (Grenier and Nelson 1995, Manley et al. 1999, Nelson and Wilson 2002, Nelson et al. 2003, Rodway and Regehr 2002). The latter variables provide cover for the nest tree at the patch scale and protection from predation, and canopy gaps are important for access. There may be a tradeoff, however, in the murrelets' requirement for easy access to nests (for jumpoff departures and stall landings); sites that are too open could potentially allow predators easy access to nests (Marzluff et al. 2000, Masselink 2001, Raphael et al. 2002b). Nest sites on forest edges have higher levels of nest predation than nests in the interior of the stand (Manley and Nelson 1999, Nelson and Hamer 1995). However, the relationship is affected by type of edge and distance to human activity (see discussion on predation and edge effects in McShane et al. 2004). Perhaps a combination of protection at the nest-tree level through horizontal and vertical foliage cover and protection at the patch level with high densities of large trees and numerous canopy layers (along with unfragmented landscapes and distance from human disturbance; see below) will provide murrelets the best protection from nest predation (Nelson et al. 2003).

Landscape-Level Associations

Marbled murrelet habitat characteristics at the landscape level have been assessed either in a descriptive sense or for predicting habitat suitability across large geographic areas. These assessments have included analyses of forest age and type, structural complexity, fragmentation indices (e.g., patch size), and topographic variables (elevation, slope, aspect, distance to marine waters). Generally, forest inventory, geographical information system (GIS), and satellite data have been used in combination with murrelet data from dawn surveys, radio telemetry, or radar to provide details on preferred landscape characteristics or to predict the past, present, and future occurrence of murrelets across large landscapes.

Age class, forest cover type, and fragmentation—
Marbled murrelets have overwhelmingly selected old-growth forests for nesting (based on actual nests and occupied behaviors). The pattern of the landscape with respect to patch size and adjacent habitat at murrelet nests and occupied sites is also important. Raphael et al. (1995), using Landsat thematic mapper imagery, found that the proportion of older aged forests (old growth and mature)

and mean patch size of older aged forests were greater in occupied than unoccupied sites in western Washington. Total watershed area and amount of remaining valley-bottom older aged forests below 600 m (1,968 ft) were also correlated with mean murrelet detections in Clayoquot Sound, British Columbia (Burger 2002b, Chatwin et al. 2000). In southern Oregon and northern California, murrelets were found to be most abundant in unfragmented old-growth forests located in a matrix of second-growth forest (Meyer et al. 2002), whereas murrelets in western Oregon nested in older aged forests surrounded by young or mature forests, but not clearcuts (Ripple et al. 2003). Overall, occupied landscapes tended to have large core areas of old growth and low amounts of overall edge (Meyer and Miller 2002, Raphael et al. 2002a).

In terms of fragmentation, murrelet detections (from surveys and radar) and nest sites have been negatively associated with increasing edge and areas of logged or immature forests. For example, murrelet nest sites in Oregon occurred in larger stands with less edge and farther from logged areas compared with random sites (Ripple et al. 2003). Additionally, numbers of murrelets entering watersheds increased with an increasing amount of core area late-seral forest (>100 m [328 ft] from an edge) and decreasing distance between late-seral patches and similar patches (Raphael et al. 2002a). Numbers decreased with increasing amounts of edge created by the juxtaposition of late-seral patches with other land cover types. In northern California, occupied sites were located in less fragmented old growth in a matrix of mature second-growth forest and in areas less isolated from other occupied sites (Meyer et al. 2002, 2004b). Murrelets also exhibited a timelag before showing a negative response to fragmentation (Meyer et al. 2002). In contrast, occupied sites had more complex patterns with more edge, a greater variety of cover types, and more complex shapes in western Washington (Raphael et al. 1995).

In British Columbia, Burger et al. (2004) showed significant positive correlations between murrelet counts and amount of suitable nesting habitat. In Clayoquot Sound, British Columbia, forest stands fragmented by logging had significantly lower detection rates and higher predator numbers (Burger 2002b, Chatwin et al. 2000). Most of the variability (91 percent) in murrelet detections in this study was explained by the combined positive effects of old-growth availability and the negative effects of logged and immature forests. In contrast, Zharikov et al. 2006 found that murrelets do not necessarily avoid fragmented landscapes and can nest successfully in old-growth fragments near clearcuts at high elevations.

The ability of models to predict murrelet habitat suitability has generally been higher by using forest inventory data than by using cover classes from remote sensing (e.g., Bahn and Newsom 2002b, McLennan et al. 2000). In general, high misclassification rates occurred in models using forest cover or GIS variables from remote sensing for predicting murrelet habitat suitability. Forest cover variables by themselves do not accurately account for stand structural attributes but are used as a surrogate when field data are not available for a wide geographic area. By relating ground-based variables with forest cover attributes in Clayoquot Sound, British Columbia, Bahn and Newsom (2002b) were better able to determine the amount of murrelet habitat (rated at four levels) and the variables most important for habitat suitability, including tree age, tree height, and basal area.

Elevation—

Murrelet nests have been found at a variety of elevations from sea level to 5,020 ft (Burger 2002a, Hamer and Nelson 1995). In the Plan area, murrelets continue to be found in low-elevation, moist forests (most within 0 to 3,400 ft, but up to 4,200 ft in the Klamath Mountains) because high elevations are generally not present, and where they are, suitable habitat does not always occur (Hamer 1995, Hamer and Nelson 1995, McShane et al. 2004, Meyer et al. 2002, Meyer et al. 2004b). Higher elevation tree species, such as silver fir (*Abies amabilis* (Dougl.) Forbes) and mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.), generally are smaller and have fewer platforms, or they lack the abundant moss layers that make the limbs suitable for murrelet nesting. In contrast, in British Columbia (especially Desolation and Clayoquot Sounds), murrelets readily nested in high-elevation forests of yellow-cedar (*Chamaecyparis nootkantensis* (D. Don) Spach.) and mountain hemlock where platforms were present (Bradley 2002, Burger 2002a, Huettman et al.,[4] Manley 1999). Lower predation was found at nests sites at higher elevations (Bradley 2002). Most nests (>80 percent) in British Columbia, however, occur below 1000 m (3,281 ft) (Manley et al. 2001, Burger 2002a), and valley-bottom forests generally included more of the structural characteristics associated with murrelet nest sites (e.g., Chatwin et al. 2000). Logging and fragmentation of much of the lower elevation forests in some areas may be related to their use of high-elevation forests (Burger 2002a, Cullen 2002). Alternatively, high-elevation forests in some areas of British Columbia may provide safer habitat than lowland areas, especially if fewer predators are present.

Slope, aspect, and moisture conditions—

Murrelet nests have been found at a variety of conditions with respect to slope and aspect. There is no evidence demonstrating that they prefer a particular aspect, but a variety of factors such as aspect, position on slope, the extent of the fog zone, and distance to water may be affecting abundance of platforms and epiphytes. For example, Huettmann et al. (see footnote 4) found that murrelets in Desolation and Clayoquot Sounds, British Columbia, nested most frequently on colder north slopes, and they suggested that these wetter slopes may have more suitable platforms based on the higher abundance of moss. Meyer et al. (2004b) also found that murrelets in northern California preferred cool slopes near the bottom of drainages, where large trees with large limbs grow abundantly. On a regional scale, occupied sites were located within the fog zone (<35 mi inland) in northern California where large coast redwood (*Sequoia sempervirens* (D. Don) Endl.) trees occur (Meyer et al. 2002, 2004a). Local variation in the presence of moss appears related to moisture levels; trees on the lower portion of slopes and in proximity to streams had more moss cover in older aged forest stands along the central Oregon coast (Nelson and Wilson 2002). At inland sites (12 to 37 mi) in southwestern Oregon and northern California, however, murrelets were absent from dry stands where platforms were abundant but moss was scarce (Dillingham et al. 1995, Hunter et al. 1998). The lack of moisture in these dry stands appears related to high daily temperatures in summer and low tree density, not aspect.

There is some evidence that murrelets prefer particular slopes. Within the Plan area, slope has generally been negatively correlated with probability of murrelet occupancy indicating that steep slopes had a lower likelihood of murrelets being present (Hamer 1996, Meyer et al. 2004b, Nelson et al. 2003). However, the probability of murrelet occupancy increasing with increasing slope was identified in one study in Washington (Hamer 1995). This result may have been related to the lack of suitable habitat at lower elevation valley bottoms and coastal gentle slopes where logging and development have fragmented habitat. In Desolation and Clayoquot Sounds, British Columbia, murrelets frequently nested on steep slopes, and breeding success appeared to increase with slope (Bradley 2002, Huettmann et al. [see footnote 4], Manley 2003). However, in other studies in Desolation Sound and other areas of British Columbia, murrelet occupancy rates showed a negative or nonsignificant association with slope (Manley 1999, Burger 2002a). Bradley (2002) suspected that factors other than slope itself, including suspected lower densities of nest predators on steep slopes, were influencing murrelet use and nest success in these areas. Huettmann et al. (see footnote 4) suggested that murrelets used steep slopes to gain access to their nests. However, murrelet access to nests appears just as easy on forest edges and in gaps as on steep slopes (Burger 2002a), suggesting that slopes are not an essential component for murrelet access.

Distance to the coast—

In general, murrelets nest in forests near the coast. Within the Plan area, most nests occur within 37 mi although murrelets range up to 55 mi inland. In Alaska, nests

[4] Huettmann, F.; Cam, E.; Bradley, R.W. [et al.]. N.d. Breeding habitat selectivity for large-scale habitat features by marbled murrelets in fragmented and virgin old-growth forest landscapes. Manuscript in preparation. On file with: F. Huettmann, Biology and Wildlife Department, Institute of Arctic Biology, University of Alaska, Fairbanks, AK 99775.

generally occur within 10 mi of the coast. A variety of factors likely influence murrelet nesting with respect to distance inland including, but not limited to, energetics, habitat availability, site fidelity, and predation pressure. Distance to the coast has been determined to be an important factor in several landscape modeling exercises. For example, Meyer and Miller (2002) and Meyer et al. (2002) found that landscapes with occupied sites and many murrelets in northern California and southwestern Oregon were located closer to marine habitat and that proximity to marine habitat was the most important limiting factor at a large landscape scale. In British Columbia, murrelets favored nesting closer to the ocean in an intact landscape compared with a landscape with a long history of logging (Zharikov et al. 2006).

Murrelets generally do not nest in forests directly adjacent to the ocean, especially in the southern portion of their range (Nelson 1997). Along the open coastline in this area, wind may affect the availability of suitable nest trees and nest platforms as well as make nests less hospitable in inclement weather. For example, perimeter forests along the ocean on Vancouver Island, British Columbia, had lower densities of trees with platforms and higher predator levels suggesting that forests directly adjacent to the coast provide poor habitat for murrelets (Burger et al. 2000, Chatwin et al. 2000). Human development in many coastal areas may also impact near-coast habitat use.

Nest Success

Low reproductive rates in murrelets are suspected to be contributing to population declines (Cam et al. 2003, Peery et al. 2004). Breeding success may play a significant role in population declines, in addition to food and habitat availability and other environmental factors (Nelson 1997, Peery et al. 2004). Rates of nest success have varied throughout the murrelets' range (0.16 to 0.46) but are generally low compared to other alcids and in most cases well below levels needed to maintain the population (Beissinger and Nur 1997, Bradley et al. 2004, Cam et al. 2003, Nelson and Hamer 1995, Peery et al. 2004). There are no data available to assess if changes in nest success have occurred over the first 10 years of the Plan. Low success rates have continued to prevail throughout the Plan area and are highest outside the Plan area in British Columbia. Most nest failures have resulted from predation (78 percent, 29 of 37 nests with known outcomes; McShane et al. 2004). Corvids (e.g., common raven [*Corvus corax*] and Steller's jay [*Cyanocitta stelleri*]) have been implicated as the primary predators of active murrelet nests, and corvids and squirrels (e.g., northern flying squirrel [*Glaucomys sabrinus*]) were identified as the key predators at artificial nests (Nelson and Hamer 1995, Raphael et al. 2002a).

Murrelets are thought to be highly vulnerable to increased nest predation associated with forest edges. The effects, however, varied with distance to edge, type of edge (artificial versus natural, abrupt versus feathered, suburban versus forested), structure of the adjacent forest, and proximity to human activity (e.g., Manley and Nelson 1999, Nelson and Hamer 1995, Raphael et al. 2002a). Early research on the success of nests with respect to edge showed that successful nests were significantly farther from forest edges than failed nests (Nelson and Hamer 1995). More recent research demonstrates mixed results, from no edge effects (Bradley 2002) to successful nests occurring farther from forest edges than failed nests (Manley and Nelson 1999) but only in proximity to human activity (Raphael et al. 2002b). For forest birds in general, predation rates were higher at abrupt edges than at feathered edges (edges with partial harvests or a different forest type; e.g., Ratti and Reese 1988) and suburban edges than forested or natural edges (e.g., DeSanto and Willson 2001, Raphael et al. 2002b). Explanations for differences in predation risk with edge type are likely related to differences in vegetation or nest concealment (vertical and horizontal) cover, use of the habitat by predators, or landscape context. Research at artificial murrelet nests in Oregon and Washington showed that nest success varied with structural complexity and proximity to human activity (reviewed in Raphael et al. 2002a). The highest survival was in simple-structured mature forests, but only when unfragmented and near human activity or fragmented and far from human activity. The lowest survival was in simple, mature forests near human activities or in old-growth forests within 1 km (0.62 mi) of human activity. Simple-structured stands adjacent to nesting areas may decrease predation at murrelet nests (Raphael et al. 2002b, Ripple et al. 2003).

Information is limited on the effects of topographic and geographic features on nest success, especially within the Plan area. In British Columbia, nest success appeared to increase with distance inland, percentage of slope, and at higher elevations (Bradley 2002; Manley 2003; Zharikov et al. 2006). Extensive telemetry research demonstrated that breeding success increased with slope and elevation in Desolation Sound. Here predator densities were three times lower than within 1 km of the ocean, suggesting that the presence of potential nest predators is much more likely at low elevations (Burger 2002a, Huettmann et al. [see footnote 4]). Bradley (2002) was not convinced of the importance of slope in nest success in Desolation Sound, stating that nest inaccessibility or some other feature associated with the cliffs and avalanche chutes in the area may be more likely to influence nest success.

Additional details on nest success and the effects of habitat fragmentation on murrelet habitat use are summarized in Lank et al. (2003) and McShane et al. (2004).

At-Sea Habitat Associations

Marbled murrelets spend most (>90 percent) of their time at sea. Their preferred marine habitat includes sheltered, near-shore waters within 3 mi of shore, although they occur farther offshore in areas of Alaska and during the nonbreeding season (up to 62 mi offshore). They generally forage in pairs on the water, but they also forage solitarily or in small groups (Carter and Sealy 1990, Evans-Mack et al. 2004, Speckman et al. 2003, Strachan et al. 1995). Large feeding aggregations are found in British Columbia and Alaska where populations are larger and prey are concentrated for longer periods. Murrelets dive and swim through the water by using their wings in pursuit of their prey; their foraging and diving behavior is restricted by physiology. They usually feed in shallow, near-shore water <30 m (98 ft) deep, which seems to provide them with optimal foraging conditions for their generalized diet of small schooling fish and invertebrates (Burger 2002a, Jodice and Collopy 1999, Strachan et al. 1995; see Burkett 1995 for prey species list). Murrelet dives generally last 15 to 60 seconds, and diving bouts last over a period of 27 to 33 minutes (Jodice and Collopy 1999, Strachan et al. 1995). They are thought to be able to dive up to depths of 47 m (157 ft; Mathews and Burger 1998). They forage in deeper waters only when upwelling, tidal rips, and daily activity of prey concentrate prey near the surface (Strachan et al. 1995).

Murrelets are highly mobile and some make substantial changes in their foraging sites within the breeding season. For example, Becker and Beissinger (2003) found that murrelets responded rapidly (within days or weeks) to small-scale variability in upwelling intensity and prey availability by shifting their foraging behavior and habitat selection within a 100-km (62-mi) area. However, many birds routinely forage in the same general areas and at productive foraging sites as evidenced by repeated use over a period of time throughout the breeding season (Hull et al. 2001, Mason et al. 2002, Whitworth et al. 2000). Murrelets in waters adjacent to the Plan area (and especially in California) are generally year-round residents near their nesting areas (Nelson 1997) and often forage repeatedly in specific, productive waters (Becker 2001).

Ultimately, however, the survival and reproductive success of seabirds is affected by their ability to find predictable high-quality foraging sites that concentrate prey (Bakun 1996). Seabirds will invariably change their foraging locations in response to variations in prey availability. During the breeding season, the distribution of murrelets at sea has been correlated with specific marine habitat characteristics that affect prey availability including the occurrence of complex tidal currents, convergence areas, upwelling, estuarine conditions, sandy substrates, and water temperatures (Ainley et al. 1995, Becker and Beissinger 2003, Burger 2002a, Lougheed 2000, Ostrand et al. 1998, Piatt and Naslund 1995). The offshore distribution of habitat decreases with decreasing latitude as the complex marine habitat structure in Alaska and British Columbia changes to a simple, straight coastline with a narrow shelf and few islands off the coasts of Washington, Oregon, and California. Within this southern area, murrelet distribution is affected by the presence of small-scale habitat features that concentrate prey, such as cape eddies, river mouths, and upwellings (Becker and Beissinger 2003, Meyer et al. 2002).

In addition, proximity to nesting flyways and nesting habitat has also influenced the at-sea distribution of murrelets in the Plan area. In southern Oregon and northern California, murrelet abundance offshore was found to be highly correlated with the presence of large, unfragmented old-growth forests in adjacent inland areas regardless of the characteristics of the marine habitat (Miller et al. 2002). Murrelets were in highest abundance when these older aged forests were contiguous with mature second-growth forest. Positive correlations with proximity to nesting flyways and habitat were also recorded off central California and south-central Alaska (Ainley et al. 1995, Ostrand et al. 1998). Becker and Beissinger (2003) showed, however, that murrelets redistributed themselves closer to nesting habitat only when both upwelling and prey availability were high. In poor prey years, they selected foraging locations farther from nesting areas or abandoned nests altogether.

Murrelets appear to be negatively affected by warm water temperatures (Ainley et al. 1995; Burger 1995b, 2000; Strong et al. 1995). The El Niño-Southern Oscillation, Pacific Decadal Oscillation, and other factors that change ocean temperatures or current flows will impact the distribution of prey, and thus alter locations for and success rates of foraging (Ainley et al. 1995). In these warm-water years, murrelets have been in lower densities in near-shore waters, and breeding attempts appear to have been significantly reduced.

Population Status and Trends

The exact size of the entire murrelet population in North America is not known. Current population estimates based on at-sea surveys (methods varying by region) are as high as 950,000 birds (McShane et al. 2004). Most of these birds occur in Alaska (about 860,000; Agler et al. 1998, Piatt and Naslund 1995) and British Columbia (55,000 to 78,000; Burger 2002a). Marbled murrelets occur in relatively low numbers off the coasts of Washington, Oregon, and California (17,300 to 33,719; 1.8 to 3.5 percent of the total population), with estimates of 5,000 birds in Washington and 6,400 to 28,000 in Oregon and northern California (table 2-1). Only about 700 birds occur between Humboldt and San Mateo Counties in California (table 2-1). Updated estimates are provided in chapter 3 (Miller et al., this volume).

Marine abundance is highest between Kodiak Island and Cook Inlet, Alaska, and along the southwest coast of Vancouver Island, British Columbia. Abundance is lowest in the Aleutian Islands and along the Alaska Peninsula, and from Washington to central California. At-sea densities vary on a temporal and geographic scale. During the breeding season, murrelets are generally found within commuting distance of their nest sites (up to 77 mi one way; Hull et al. 2001, Nelson 1997, Whitworth et al. 2000). During the nonbreeding season, they disperse more widely in most areas (especially in Alaska), and their distribution is dependent on the availability of winter foraging habitat and prey distribution.

Few data have been available with which to access the trends in populations of marbled murrelets in North America. Historically, populations of murrelets are thought to have declined significantly within the Plan area (e.g., Carter and Erickson 1992, Ralph 1994, Ralph et al. 1995b, USFWS 1997). More recently, major declines (22 to 73 percent) over a decade or more have been documented in British Columbia, Washington, Oregon, and specific areas of Alaska (table 2-2). Strong (2003) documented an abrupt decline along the central Oregon coast during the early 1990s (>50 percent), although near-shore densities have not changed appreciably since 1997. In British Columbia, the number of murrelets in Clayoquot and Barkley Sounds declined 22 to 50 percent between 1982 and 1996 (Burger 1995b, 2002a; Chatwin et al. 2000; Kelson et al. 1995;

Table 2-1—Marbled murrelet population estimates (and standard errors) based on boat surveys between 1989 and 1998[a]

Location	Estimates ± SE (when available)		
Washington:	5,000[b]		
Outer coast and straits	2,400[b]	3,400-3,600[c]	
Outer coast	2,400[d]		
Puget Sound	2,600[d]		
Oregon:	14,842-22,252[e]	6,400-6,800[c]	
Southern	3,495 + 243[f]		
California:			
Northern	5,704 ± 342[g]	3,102-4,798[h]	5,142[i]
Central	763 ± 125[g]		717 ± 93[i]

[a] Before the Plan surveys; boat-based unless otherwise noted.
[b] Speich et al. 1992.
[c] Aerial surveys, Varoujean and Williams 1995.
[d] Speich and Wahl 1995.
[e] Strong et al. 1995.
[f] Strong 1996.
[g] Ralph and Miller 1995.
[h] Oregon to Point Arena, Strong et al. 1997.
[i] Estimates for northern California done by region where SE ranged from 3 to 8 percent; Miller et al. 2002.

Table 2-2—Marbled murrelet population trends from marine surveys, 1972-2003 [a]

Area	Period	Trend	Source
Alaska [b]	1972-1991	67-73% decline	Klosiewski and Laing 1994
	1972-1993	Decline	Agler et al. 1999
	1984-1998	No clear trend	Irons et al. 2000
	1989-1998	No recovery after *Exxon Valdez* spill	Lance et al. 2001
British Columbia	1982-1993	40% decline, Clayoquot Sound	Kelson et al. 1995
	1982-1996	22% decline, Clayoquot Sound	Kelson and Mather 1999
	1987-1993	50% decline, Barkley Sound	Burger 1995b
	1996-2000	Possible decline, Clayoquot Sound	Mason et al. 2002
	1982-2002	22-44% decline	Burger 2002a
Washington	1972-1993	Possible decline	Speich and Wahl 1995
	1996-1999	No clear trend, outer coast	Thompson 1997
	1978-2003	51% decline, Puget Sound	J. Bower [c]
Oregon	1992-1996	>50% decline, central coast	Strong 2003
	1997-2003	No clear trend	Strong 2003

[a] Prior to standardized Plan monitoring.
[b] All from Prince William Sound, Alaska.
[c] Bower, J. 2005. Personal communication. Assistant Professor, Fairhaven College, Western Washington University, 516 High Street, Bellingham, WA 98225.
Adapted from Lank et al. 2003.

Kelson and Mather 1999; but see Burger 2002a for potential complicating effects of warm oceans). Subsequent surveys suggest a continuing decline and have confirmed murrelets are at a lower abundance than in the early 1980s (Burger 2002a, Mason et al. 2002). In northern Puget Sound, Washington, murrelet populations may have declined 51 percent since the late 1970s (J. Bower[5]). A long-term data set from Prince William Sound demonstrates a significant decline in murrelet numbers since 1972 (50 to 73 percent; Agler et al. 1999, Klosiewski and Laing 1994, Kuletz et al. 1997). These declines have been attributed to loss of nesting habitat from logging, bycatch, the *Nestucca* and *Exxon Valdez* oil spills, and increases in water temperatures, which affected prey availability.

Demographic modeling has also projected murrelet population declines. Beissinger (1995) and Beissinger and Nur (1997) estimated an annual decline of 4 to 7 percent of the population within the Plan area. More recently, McShane et al. (2004) projected a mean annual rate of decline of 2 to 6 percent per decade over the next 40 years based on a more detailed demographic modeling procedure. They further projected a 16-percent probability of extinction of the population in the Plan area over 100 years, with birds in California and Oregon disappearing completely and only 45 birds remaining in Washington. These models are based on numerous assumptions, including constant fecundity and survival rates. These models do not account for increases in suitable habitat or changes in the carrying capacity of the habitat that might result from habitat recovery over time (as expected under the Plan). Peery et al. (2002) found that populations of murrelets in the Santa Cruz area (Zone 5) appear stable even though demographic models project a declining population. They suggested that this population may be supported by recruitment of individuals from outside the area.

In addition to at-sea counts and demographic modeling, it has recently been demonstrated that counts with radar have the potential to detect changes and monitor local inland populations over time (Bigger et al., in press; P. Arcese[6]). Radar counts have the added benefit of determining the overall carrying capacity at the drainage level and linking the amount of suitable nesting habitat to population counts of birds flying into drainages (see “Landscape-level Associations” above; Burger et al. 2004, Raphael et al. 2002a).

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Metric Equivalents

When you know:	Multiply by:	To get:
Inches (in)	2.54	Centimeters (cm)
Feet (ft)	.305	Meters (m)
Miles (mi)	1.609	Kilometers (km)

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Chapter 3: At-Sea Monitoring of Marbled Murrelet Population Status Trend in the Northwest Forest Plan Area

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Abstract

Miller, Sherri L.; Ralph, C. John; Raphael, Martin G.; Strong, Craig; Thompson, Chrtopher W.; Baldwin, Jim; Huff, Mark H.; Falax, Gary A. 2006. At-sea monitoring of marbled murrelet population status and trend in the Northwest Forest Plan area. In: Huff, Mark H.; Raphael, M.G.; Miller, S.L.; Nelson, S.K.; Baldwin, J., tech. coords. Northwest Forest Plan—The first 10 years (1994-2003): status and trends of populations and nesting habitat for the marbled murrelet. Gen. Tech. Rep. PNW-GTR-650. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 31-60. Chapter 3.

One objective of the Marbled Murrelet Effectiveness Monitoring Plan for the Northwest Forest Plan (the Plan) is to monitor changes in marbled murrelet abundance throughout the Plan area, by using a unified and scientifically valid sampling design. This chapter provides an overview of the steps used to develop the sampling design, details of the design, and results of monitoring from 2000 to 2003.

Population-monitoring surveys in the Plan area began by using the new sampling design in 2000. Surveys have been conducted through the efforts, funding, and cooperation of federal and state governments, contractors, and private industry. We have conducted over 750 primary sampling unit surveys on about 16,000 mi of transects, and recorded over 18,000 murrelet observations in the target population zones, a 3,400-square-mile offshore area.

The total population estimate for the coastal waters adjacent to the Plan area for 2003, the most recent year, was 22,200 murrelets with a 95 percent confidence interval of 18,100 to 26,400. We estimated the highest density of birds at the zone level over all 4 years to be 12.24 birds per square mile, in Zone 3. As expected, densities varied within zones with two- to eightfold differences between strata. We observed the lowest densities of birds, 0.14 to 0.73 birds per square mile in Zone 5. The estimated percent standard error of the population estimates is a measure of the variability in our sampling. This error of the density for all zones combined varied by year between 9.5 and 14.2.

Our results did not detect a decrease in the size of the target population over the 4 years of monitoring at the 5 percent significance level. Our measure for assessing this monitoring program is its power to detect changes in the mean density (and the resulting mean total population) of murrelets over time. When all of the zones are combined, we would have an 80- to 95-percent chance of detecting a 3- to 4-percent annual decrease with a 10-year sampling period. The change we could detect in 10 years, with 80- to 95-percent power, differs among the five zones. For all zones combined, in 15 years we could detect an annual decrease of 2-percent with 95-percent power. In only 10 years, we could detect a 3-percent annual decrease with 80-percent power. As the Effectiveness Monitoring effort continues, the consequences of errors in estimating trends should be evaluated

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and goals established. In addition to setting population targets, management response to observed trends should be considered.

Background

The approach developed by Madsen et al. (1999) for marbled murrelet effectiveness monitoring under the Northwest Forest Plan (hereafter, the Plan) recommended assessing population abundance under a unified sampling design at sea. Inland, the goal was to establish a credible baseline of nesting habitat. The trends in both population abundance and nesting habitat would be tracked over time. The goal was to determine if population trends could be inferred from the amount and distribution of nesting habitat and thereby reduce or eliminate the monitoring of murrelet populations offshore. Oceanographic conditions, predator abundance, and juvenile and adult survival are among the many factors that affect murrelet populations. Although we are now estimating trends in the amount and distribution of nesting habitat (see Huff et al. and Raphael et al., chapters 4 and 5, this volume), until a relationship between habitat and population trends is established that incorporates the additional factors affecting murrelet abundance, offshore population monitoring will be our primary murrelet monitoring tool.

With our current understanding of marbled murrelet ecology, there is general consensus that populations are best assessed at sea. Because of the cryptic nature of the species in its nesting habitat, high in forest canopies (Madsen et al. 1999, Ralph et al. 1995), crepuscular (dawn and dusk) inland activity, and dispersed, variable nesting locations, population estimation is not feasible at inland nesting areas. Use of radar at coastal locations was considered as a monitoring technique. Research using radar for this purpose was underway when we began developing our monitoring plan, but the technique had not yet been evaluated. Although radar now appears promising for monitoring at a watershed scale Bigger,[6] and potentially for establishing inland habitat relationships, at best, it would compliment offshore surveys, rather than replace them.

This chapter provides an overview of methods used to assess the status and trend of marbled murrelet populations under the Plan and results of monitoring from 2000 to 2003.

In 1998, a team of experts was assembled by the U.S. Fish and Wildlife Service to design and implement a population monitoring protocol.[7]

One objective in the *Marbled Murrelet Effectiveness Monitoring Plan for the Northwest Forest Plan* (Madsen et al. 1999), was to track the temporal change in abundance and reproductive rates throughout the Plan area. We reviewed the methods being used to measure reproduction: age ratios determined from the number of juveniles and adults observed at sea, observation of active nests, and locating nests after the breeding season to identify nest outcome. Productivity measured at sea is the most cost-effective method; however, results must incorporate temporal and spatial distribution of young and adults, relationship of age ratios to fledging rates, fledgling survival, and other factors. We determined that all the methods needed further research before results could be interpreted with confidence. We focused our efforts on monitoring population changes. Many research programs have continued to study marbled murrelet demographic

[6] Bigger, D.; Peery, M.Z.; Baldwin, J.; Chinnici, S.; Courtney, S.P. [In press]. Power to detect trends in marbled murrelet populations using audio-visual and radar surveys. Journal of Wildlife Management. 70(2): 492-503.

[7] Team members included Naomi Bentivoglio, Team Lead, USDI Fish and Wildlife Service; Steven R. Beissinger, Professor, University of California, Berkeley; Jim Baldwin, Statistician, USDA Forest Service, Pacific Southwest Research Station; Tim Max, Statistician, USDA Forest Service, Pacific Northwest Research Station; Sherri Miller, Wildlife Biologist, USDA Forest Service, Pacific Southwest Research Station; Ken Ostrom, GIS/Database Specialist, U.S. Fish and Wildlife Service; C. John Ralph, Research Ecologist, USDA Forest Service, Pacific Southwest Research Station; Martin G. Raphael, Research Wildlife Biologist, USDA Forest Service, Pacific Northwest Research Station; Craig Strong, Consulting Biologist, Crescent Coastal Research; Chris Thompson, Research Scientist, Washington Department of Fish and Wildlife. Some team memberships changed over the period of design and implementation.

measures, and the efficacy of adding a productivity component to population monitoring should be reevaluated in the future.

The approach adopted by the team for developing a popula-tion monitoring design included several steps. We reviewed survey methods and sampling designs used to monitor murrelets in North America since 1989. Because some members of the team had conducted a large portion of the past population surveys, data were available to analyze specific aspects of methods and results. We also used past data to explore potential sampling designs by using computer simulated populations and samples. A variety of analysis techniques for estimating population size were reviewed and considered in the context of murrelet biology and Plan objectives. Tests of the suggested methodologies were conducted during the 1998 and 1999 field seasons. We reached consensus on the new methods, and the sampling design was implemented in 2000.

Our sampling strategy, including the design and analysis procedures, is documented in a series of marbled murrelet effectiveness monitoring annual reports (available at http://www.reo.gov/monitoring/murrelet/index.htm): mostly reported in Bentivoglio et al. (2002), with subsequent changes in Huff (2003), and compiled comprehensively in Raphael et al (n.d.).[8] that is intended to augment the present paper. Here, our objective is to provide a summary of these methods presented elsewhere and to report the monitoring results from 2000 to 2003. Information in this report on trends is preliminary.

Sampling Design

Target population

The team identified the target population as those birds from the Canadian border south to San Francisco Bay, the area associated with the Plan. We subdivided the target population into the five marbled murrelet conservation zones (figs. 3-1 through 3-6) identified in the Marbled Murrelet Recovery Plan (USFWS 1997, Huff, chapter 1, this volume, fig. 1-1) in this area. A sixth conservation zone (Zone 6) is located outside of the Plan area, and was not sampled. Within the five zones, we further identified the target population as those birds in navigable, near-shore waters within 5 mi (8 km) of shore. The offshore target population boundaries differed by zone (table 3-1) and were selected after reviewing available data on murrelet marine distribution (table 3-1). In general, few murrelets, representing a very small proportion of the population, were observed beyond the selected distances for each zone (Ainley et al. 1995, Ralph and Miller 1995, Speich and Wahl 1995, Strong et al. 1995, Varoujean and Williams 1995), and we do not expect discernible increases in these numbers. The inshore boundary was defined by the closest distance from shore that permitted safe boat travel. In Zones 2 through 5, the inshore boundary was 0.217 mi (350 m) (table 3-1), with a few adjustments for dangerous, rocky sections of coast. In Zone 1, where water depth increased more rapidly, and surf zones are narrow, the inshore boundary was 0.186 or 0.062 mi (300 or 100 m). Mid-May through late July is when breeding birds at sea are likely to be associated with inland nesting habitat in the Plan area (Nelson 1997). We established 15 May through 31 July as our sampling period for population monitoring. Because we are unable to visually distinguish breeding from nonbreeding birds during surveys, we included all birds in our target population. The proportion of the population that breeds in any one year is generally not known, but estimates are from about 30 to 85 percent (Becker et al. 1997, Hebert and Golightly 2002, McFarlane Tranquilla et al. 2003).

Stratification

Within each zone, existing data were used to identify large geographic areas with different densities of murrelets along the coast. Given the expected homogeneity within each of these areas, each was designated as a separate stratum (table 3-1). Strata with extremely low densities were sampled less often. We used all data within a zone to estimate the population for that zone.

[8] Raphael, M.G., Bentivoglio, N., Baldwin, J., Huff, M.; Max, T.; Miller, S.L.; Ostrom, K.; Ralph, C.J.; Strong, C.; Thompson, C.; Young, R. [N.d.]. Regional population monitoring of the marbled murrelet: field and analytical methods. Manuscript in preparation. On file with: Martin G. Raphael, USDA Forest Service, Pacific Northwest Research Station, 3625 93rd Ave. SW, Olympia, WA 98512.

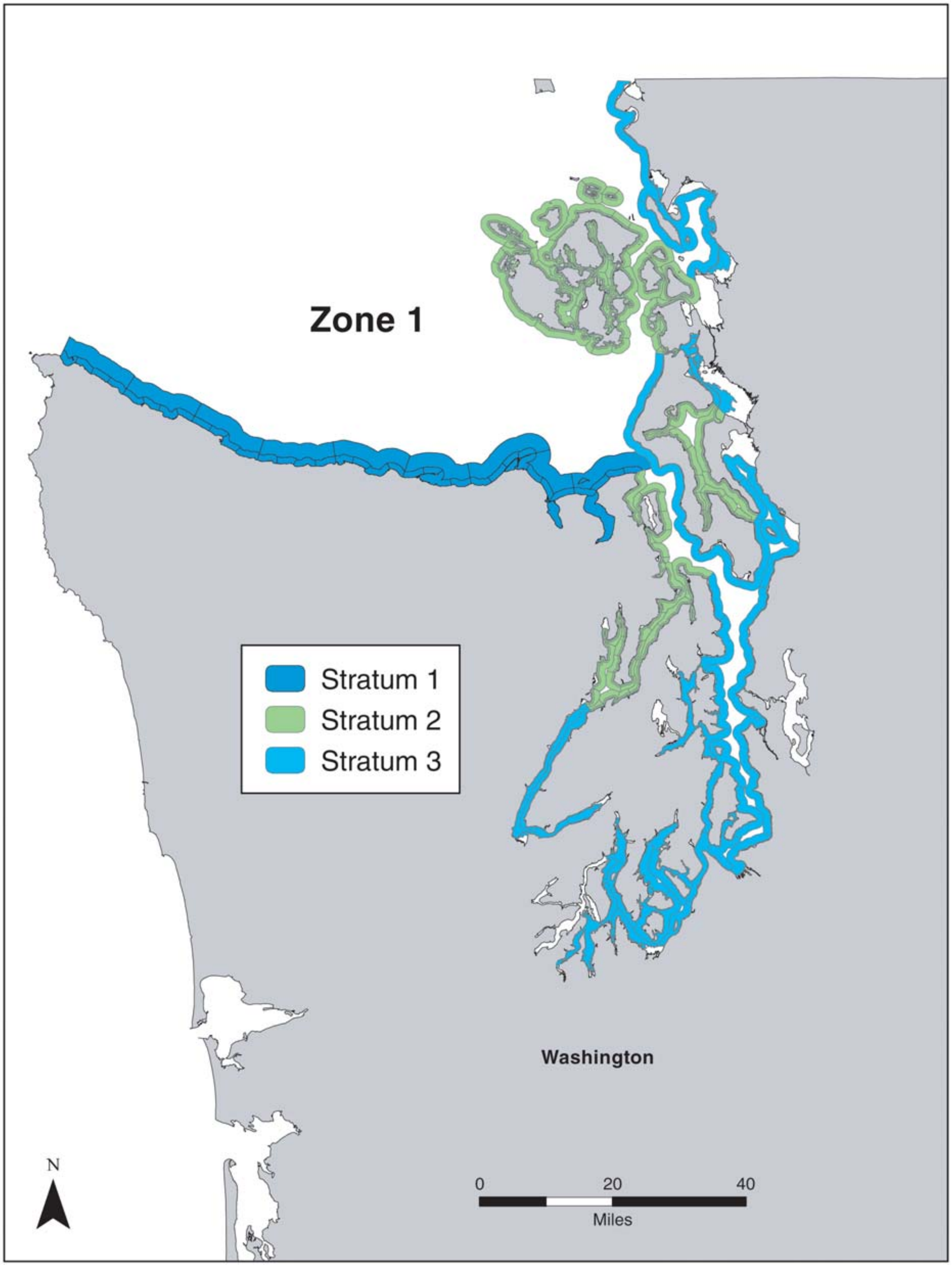

Figure 3-1—Marbled murrelet conservation Zone 1 Primary Sampling Units and strata are identified.

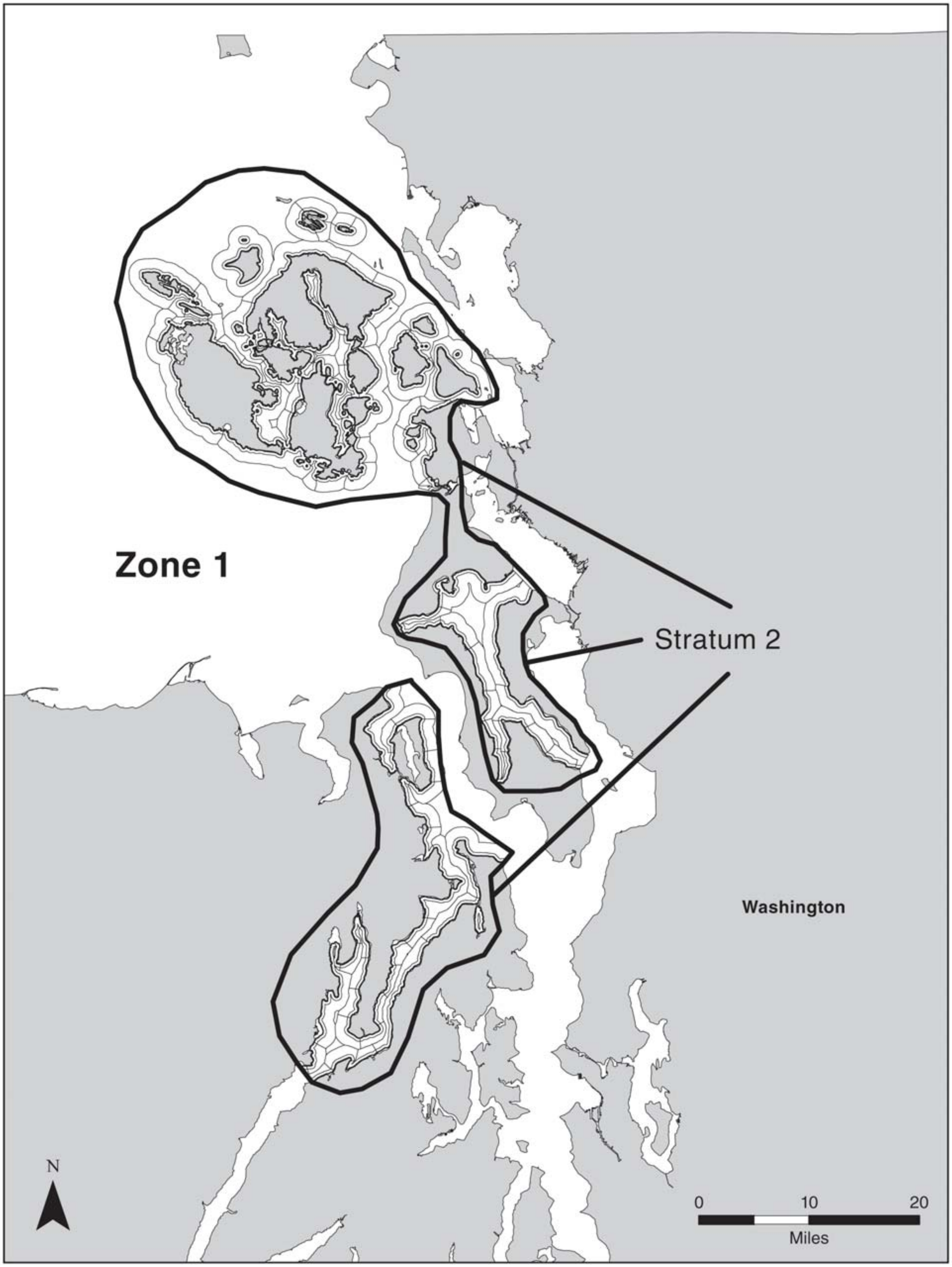

Figure 3-2—Marbled murrelet conservation Zone 1, stratum 2 with detail. Primary Sampling Units and strata are identified.

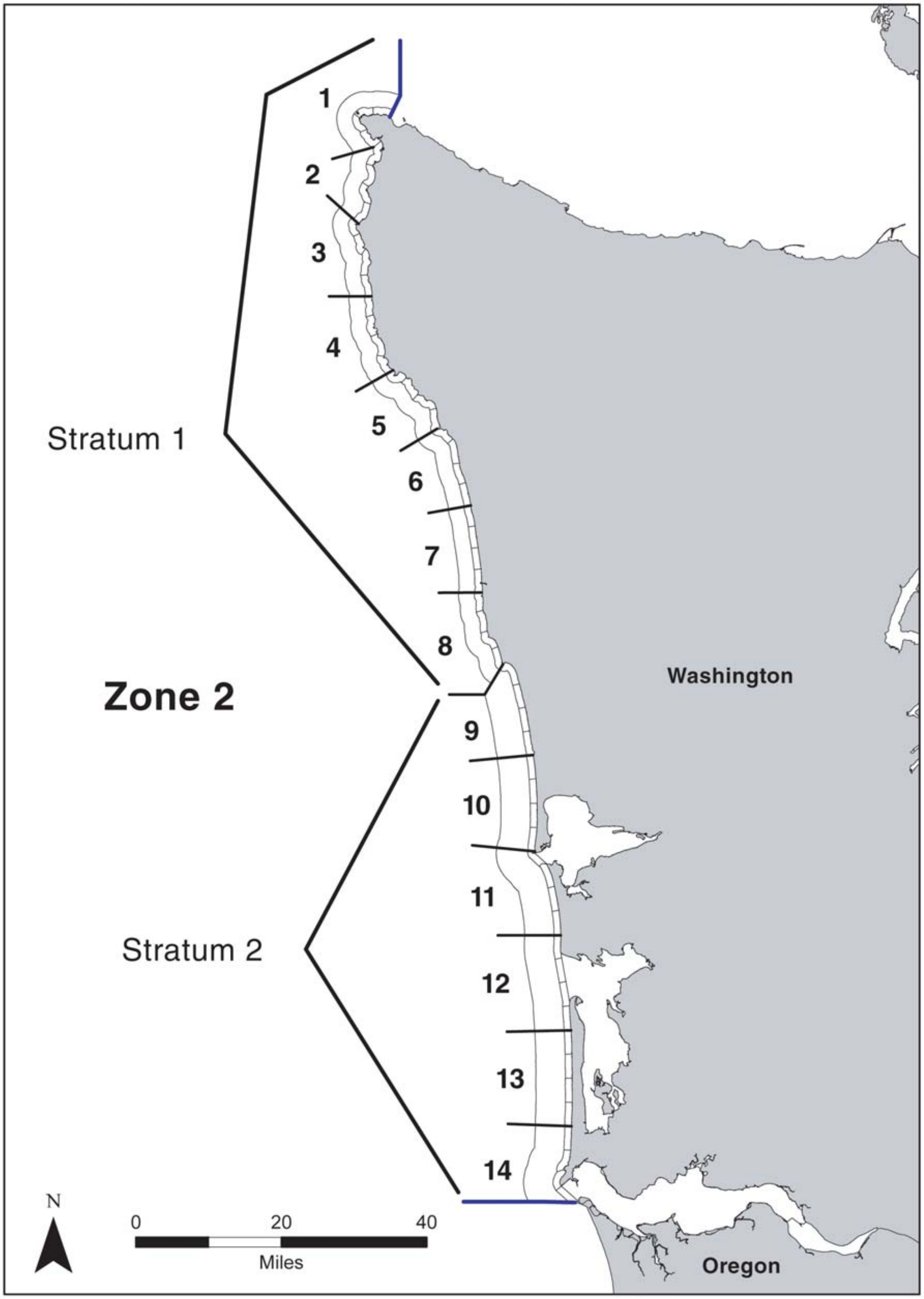

Figure 3-3—Marbled murrelet conservation Zone 2. Primary Sampling Units and strata are identified.

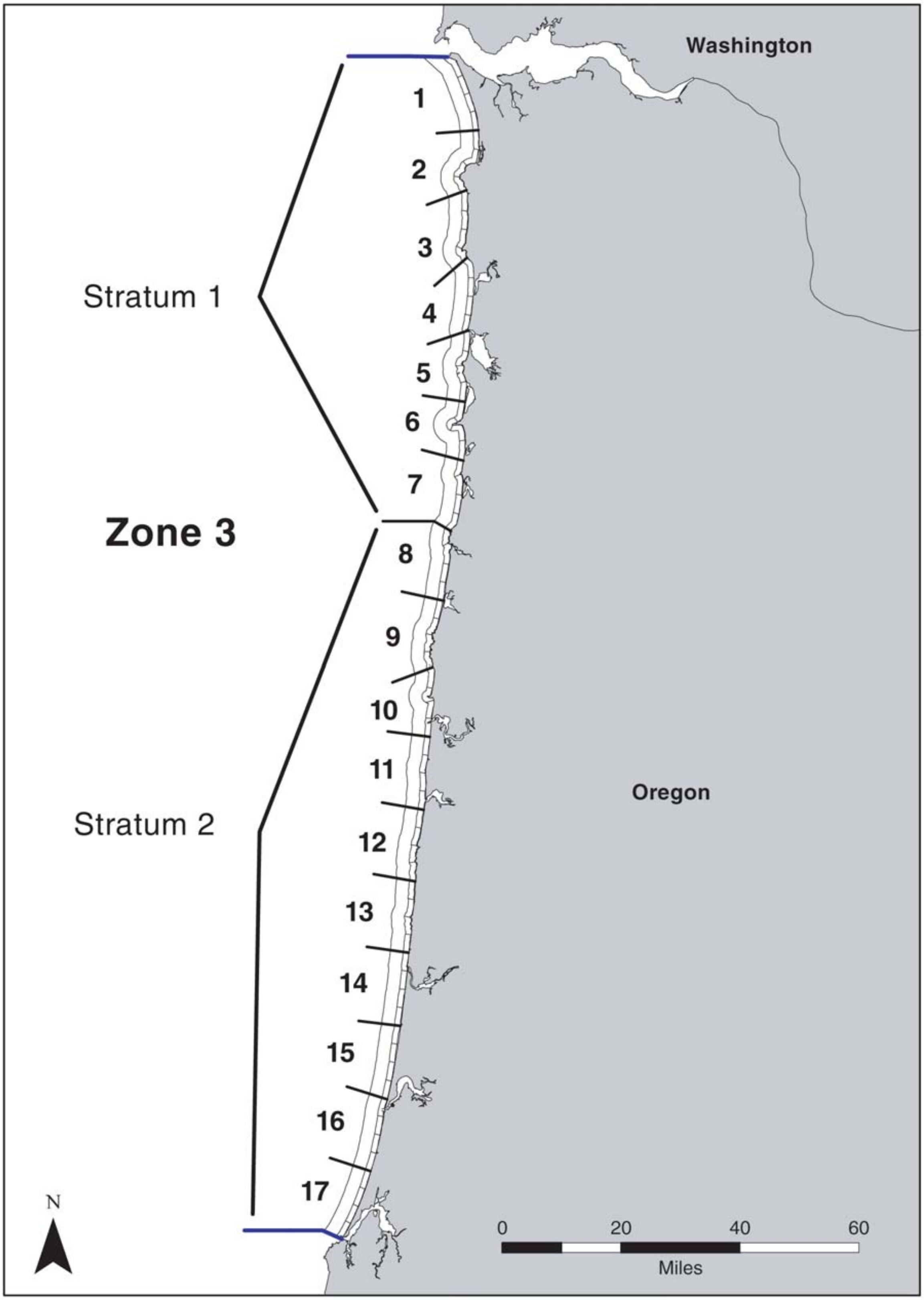

Figure 3-4—Marbled murrelet conservation Zone 3. Primary Sampling Units and strata are identified.

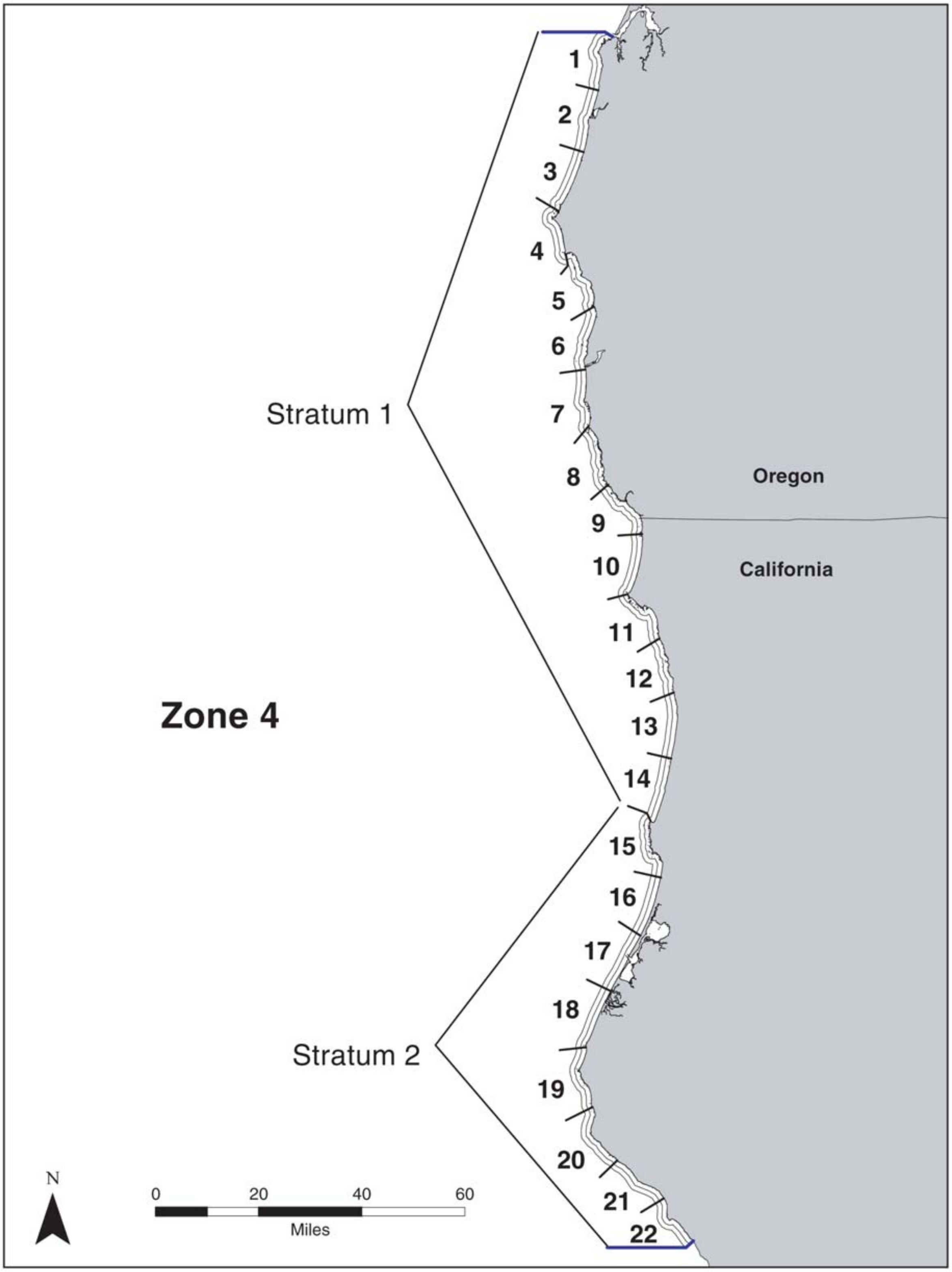

Figure 3-5—Marbled murrelet conservation Zone 4. Primary Sampling Units and strata are identified.

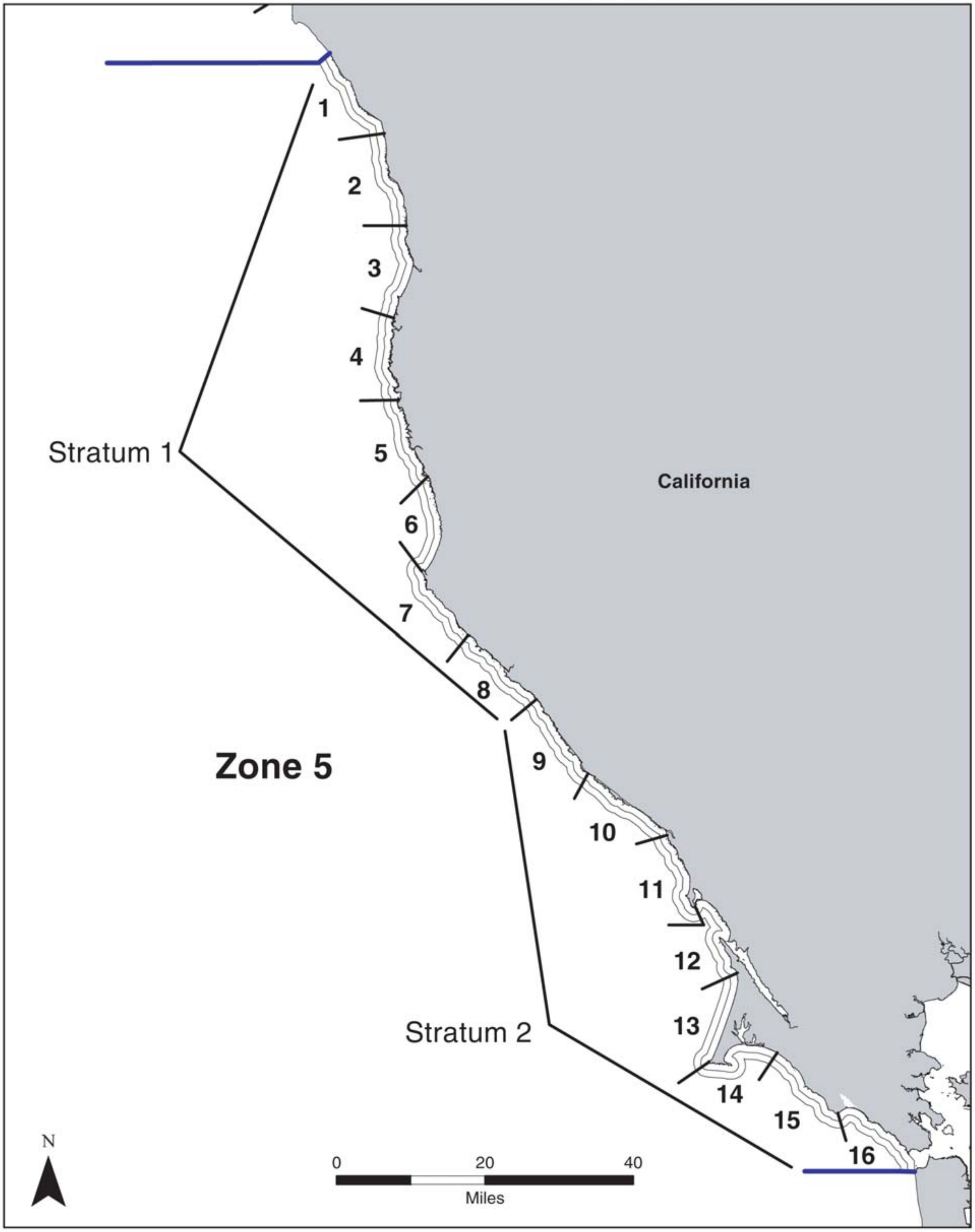

Figure 3-6—Marbled murrelet conservation Zone 5. Primary Sampling Units and strata are identified.

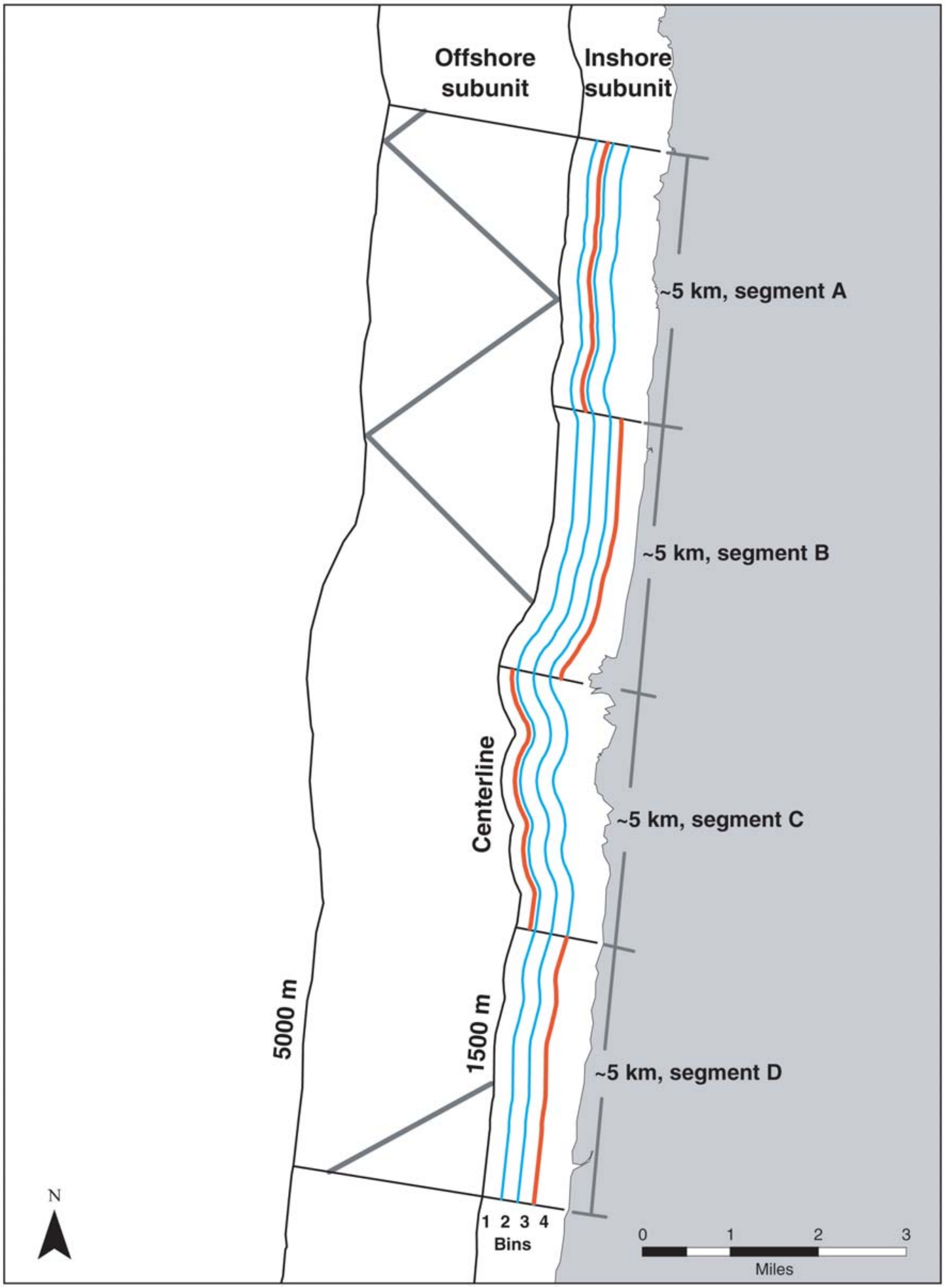

Figure 3-7—Marbled murrelet primary sampling unit with inshore and offshore subunits, showing parallel and zigzag transects. The inshore subunit is divided into four equal-length segments (about 5 km each) and four equal-width bins (bands parallel to [and at increasing distances from] the shore). One bin is selected (without replacement) for each segment of transect.

Table 3-1—Marbled murrelet effectiveness monitoring population sampling design overview

	Conservation zone (figure 1-1)				
Attribute	**1**	**2**	**3**	**4**	**5**
Target population	Nearshore (within 4.96 mi) marine waters of zones 1 - 5				
Geographic strata	1. Strait of Juan de Fuca	1. North portion of zone	1. North portion of zone	1. North portion of zone	1. North portion of zone
	2. San Juan Islands and selected portions of Puget Sound	2. South portion of zone	2. South portion of zone	2. South portion of zone	2. South portion of zone
	3. The remainder of San Juan Islands and Puget Sound				
Primary sampling unit (PSU) (figs 3-1 and 3-2)	~12.4 mi section of coastline with inshore and offshore subunits				
Area of inference by geographic stratum (miles from shore)	1. 0.19 – 3.11 2. 0.06 – 1.24 3. 0.06 – 1.24	1. 0.22 – 3.11 2. 0.22 – 4.97	1. 0.22 – 3.11 2. 0.22 – 3.11	1. 0.22 – 1.86 2. 0.22 – 1.86	1. 0.22 – 1.86 2. 0.22 – 1.86
Centerline distance by stratum (miles from shore)	1. 0.93 2. 0.31 3. NA[a]	1. 0.93 2. 0.93	1. 0.93 2. 0.93	1. 1.24 2. 1.24	1. 1.24 2. 1.24
PSU selection	Random selection without replacement within each geographic stratum and spread over time and space to the maximum extent feasible				
Total PSUs within zone	98	14	17	22	16
Stratum 1	9	8	7	14	8
Stratum 2	42	6	10	8	8
Stratum 3	47	NA	NA	NA	NA
Total area of zone per mi^2	1,349	652	610	450	342
Stratum 1	324	249	249	285	171
Stratum 2	462	361	361	165	171
Stratum 3	563	NA	NA	NA	NA
Time of year	Mid-May to end of July				
PSU[b] subsampling (fig. 3-2)	Four, 3.11-mi parallel transects in nearshore subunit; zigzag offshore[c]				

[a] In stratum 3 of Zone 1, we do not distinguish the nearshore and offshore subunits and follow a zig-zag transect throughout each PSU.

[b] Primary sampling unit is an area of about 12 mi in length along the coast and 1.24 mi, 1.86 mi, 3.10 mi, or 4.96 mi in width off the coast.

[c] Zig-zag length differs by zone.

With additional sampling, separate density estimates with adequate precision could be obtained for each geographic stratum within zones. This could help refine information about offshore populations and the amount and distribution of inland habitat at scales smaller than an entire conservation zone. In Zone 4, the Pacific Lumber Company[9] implemented a Habitat Conservation Plan under the Endangered Species Act that included a murrelet monitoring component (Pacific Lumber Company 1999). Additional surveys were funded for 2000 through 2003 that allowed a separate population estimate in the southern stratum of the zone based on a full survey effort.

Primary Sampling Units

Spatial definition of a Primary Sampling Unit—
A primary sampling unit (PSU) is a roughly rectangular area along approximately 12.4 mi (20 km) of coastline. The width of the PSU is the distance between the inshore and offshore boundaries (fig. 3-7); width differed by zone and stratum (table 3-1) (see Bentivoglio et al. 2002 and Raphael et al. [see footnote 9] for boundary selection details). The PSUs meet end to end along the shore without any gaps.

Each PSU consists of one inshore and one offshore subunit, divided by the centerline (fig. 3-7). We designated inshore and offshore subunits based on murrelet densities. Examination of past data showed decreasing murrelet density with distance from shore (Ralph and Miller 1995, Raphael et al. 1999, Strong et al. 1995) with about 95 percent of the observations in the inshore subunit area. Our sampling design allows us to sample with more effort in the inshore subunit where most of the birds are foraging and continue to sample, with lower effort, the low-density, offshore subunit to assure detection of any future shift in distribution.

[9] **Pacific Lumber Company. 1999.** Habitat conservation plan for the properties of the Pacific Lumber Company, Scotia Pacific Holding Company, and Salmon Creek Corporation. Available from Scotia Pacific Company, P.O. Box 712, Scotia, CA 95565.

Temporal definition of PSU—
We elected to use only PSU surveys conducted on a single day. Wind, fog, mechanical problems, or other unforeseen difficulties sometimes prevented a crew from completing a PSU survey. Partial PSU surveys were not used for analysis if less than 75 percent of the transect length was completed. If a boat completed more than one PSU survey in a day, all the surveys were used for analysis.

Sample size per zone—
Each conservation zone or stratum where a population estimate was desired had a target sample size of 30 PSU surveys. We based our target on analyses that demonstrated reasonably low coefficients of variation as total transect length approached 373 mi (600 km), or 30 PSUs.

Selecting PSUs for sampling—
The entire coastline of the zones was segmented into 167 PSUs (figs. 3-1 through 3-6), with the number of PSUs in each zone differing (table 3-1). Within each zone, we randomly selected 30 PSUs, without replacement. In zones with less than 30 PSUs (Zones 2 through 4), once all PSUs were selected, they were available for additional sets of random selections until 30 samples were reached. In Zone 1, with 98 PSUs, the set of PSUs that were selected for the 2000 field season were resampled each year. In Zone 5, stratum 2, four PSUs were randomly selected from the eight PSUs for resampling each year. Resampling of only the selected PSUs reduces variance in our estimate of population trend. Of the 167 PSUs available throughout the target area, we sampled about 160 individual PSUs each year, including those that were sampled two or more times.
In some years a few of the selected PSUs could not be sampled because of unsafe weather conditions. The sampling design and sample selection process allow for reduced sample size for some stratum or years, although this would likely increase the error associated with the estimates.

The sampling order followed the random selection order, and the sampling days were distributed across the season. Although the selection of PSUs was initially random, field sampling was subject to logistical constraints, such as the distance between ports, weather, and mechanical difficulties. These logistics resulted in clustered samples, that is, samples that were taken more closely together in space and time than random choice would have dictated. We accounted for these clustered observations when estimating density (see the "Analysis" section for details).

Transect layout within PSUs—
The PSUs were sampled by using parallel transects in the inshore subunit and zigzag transects in the offshore subunit (fig. 3-7). In the inshore subunit, the length of the PSU (approximately 12.4 mi (20 km)) was divided into four approximately 3-mi (5-km) transect segments parallel to shore. The width of the subunit was divided into four bins parallel to shore and of equal size. One transect was randomly placed in each bin (without replacement) ensuring that transects were distributed spatially at different distances from shore (fig. 3-7) (See Bentivoglio et al. 2002 for further details)

In the offshore subunit, a zigzag transect traversed the entire width of the subunit (fig. 3-7) for a portion of the PSU's length, or in some cases, the entire length. The zigzag configuration will sample across the density gradient associated with distance from shore, while allowing less effort per area in this low-density subunit. A random starting point for the zigzag transect line is selected for each PSU survey.

The length of the zigzag transect in each zone was approximated by using a formula that calculates the optimal allocation of effort among the two subunits (Cochran 1977) given by:

$$r = \frac{a_1}{a_2} \cdot \sqrt{\frac{\lambda_1}{\lambda_2}}$$

where a_1 and a_2 are the areas of each of the inshore and offshore PSU subunits, respectively, with mean densities of birds, λ_1 and ˜λ_2, observed in each collection of subunit transects and assumed to follow a Poisson distribution. This ratio (r) is the product of the area ratio and the square root of the density ratio. The resulting value "r" represents the optimal ratio of inshore to offshore transect length, that minimizes variance of the weighted average of murrelet density for the two subunits within each zone.

Line Transect Sampling

The line transect sampling method was used to estimate murrelet density (number of murrelets per unit area per day), and, ultimately, population size. We recorded the perpendicular distance of each murrelet observation (or group of murrelets) from the transect line for use in the program DISTANCE (Buckland et al. 1993, 2001; Thomas et al. 1998, 2004), which selects a mathematical function to describe the effect of distance on numbers of groups of birds detected. This method makes some important assumptions, including that birds near the line are not missed, the birds' response to the boat does not affect an observer's ability to detect them, and the distance of objects from a transect line is accurately estimated. Average dive times of 14 to 44 seconds have been reported for murrelets by various studies (Strachan et al. 1995), with a maximum dive time of 115 seconds. By maintaining boat speeds between 8 and 15 knots, birds diving in response to the boat should emerge at the surface and be available for detection before the boat has passed. Observer accuracy is assessed during training and during surveys to calibrate distance estimates and control for variation. We are continuing to examine the potential effect of these assumptions on our estimates (Brennan 2000, Mack et al. 2002, Raphael et al. 1999).

Observer Methods and Training

During surveys, two observers survey 90° arcs on their side of the boat starting from the bow. Observers scan continually, slowing their pace slightly at the bow of the boat. More effort is thus expended watching for birds close to the line ahead of the boat (within 45° of the line of travel) to reduce the risk of missing birds located close to the transect line. Observers estimate the perpendicular distance of each murrelet (or the center of a group of murrelets less than 4 ft (1.5 m) apart) from the transect line. Binoculars are used for species verification, but not for the original bird sighting. For most surveys, observers record information into tape recorders for subsequent transcription to survey forms. In some surveys, observations relay sightings by microphones in headsets to a person in the boat cabin who enters data directly onto a computer. Additional details and a survey form and the codes used can be found in Bentivoglio et al. (2002).

Observer training is a key focus of our quality control and assessment procedures. New observers spend 2 to 4 weeks with an experienced trainer learning techniques for bird identification, distance estimation, scanning, navigation, and safety procedures. Returning observers spend time with a trainer renewing their skills before surveys begin. Simultaneous surveys are conducted by the trainer and observers to help reduce observer variation. Each observer must successfully complete a series of assessment drills to test their survey, boating, and safety skills.

To estimate densities, the observer must accurately estimate the perpendicular distance from the transect line to birds detected from the boat. Training in distance estimation is conducted first on land, then on the water. Laser rangefinders are used for training and also for calibration and testing of observers' distance estimates before each survey. Distances to stationary buoys, crab pot buoys, or a small buoy or float tossed from the boat are estimated by the observer and the distance then measured with a rangefinder when the boat reaches a position perpendicular to the object. Testing continues until distance estimates are within 15 percent of measured distances.

Analysis

Overview

Statistically defensible estimates of average marbled murrelet density (average daily numbers of birds per square mile for the target period) for the target population, with associated estimates of precision, were produced for each conservation zone separately and also for the entire target population, consisting of all zones combined. This estimation required integration of design, implementation, and analysis. In this section, we describe the analytical methods required to produce the desired estimates.

In general terms, we produced a separate estimate of average daily density (numbers of birds per square mile), with an associated estimate of precision based on bootstrap resampling methods, for each geographic stratum. All zones had two or three strata (table 3-1). First, standard methods for stratified sampling (Cochran 1977, Sokal and Rohlf 1981) produced estimates for zones and overall estimates for the entire target population. All basic estimation within strata was done for density first. We then extrapolated density estimates, and associated estimates of precision, to the total area in each stratum. With this, we estimated the average number of birds for the target period, with associated estimates of precision, by zone (and for all zones combined). The remainder of this section summarizes these various procedures. (Additional details are documented in Bentivoglio et al. 2002).

Estimates of Density Within Strata

Two main parameters were required for using the DISTANCE program (Thomas et al. 1998, 2004) to summarize the data.

- Specifications for truncating observations of birds at large distances from the transect line.
- Selecting the method for determining which detection function to use.

For truncating data, we eliminated the 5 percent of observations in each stratum that were the greatest distance from the boat. These observations were eliminated because they have negligible effect on density estimates and can cause unnecessarily complex models of the detection function.

In DISTANCE, we chose two model types, half-normal and uniform, for selecting the detection function curve by using Akaike Information Criteria (AIC) (Burnham and Anderson 1998). Perpendicular distances were grouped into 66-ft (20-m) distance bins prior to analysis.

For each zone, we pooled all observations from inshore and offshore subunits then used DISTANCE to obtain estimates of the probability of a bird being detected on the transect line ($f(0)$), estimated from the probability density function of detection distances ($f(x)$) and the mean number of birds per group ($E(s)$). A size bias regression model was used to incorporate into the detection function the effect of differences in detectability caused by group size. Also from the program we obtained the observed encounter rate (*ER* = number of groups of birds observed per mile of transect) for each PSU subunit (inshore and offshore) survey. Density for each PSU subunit survey was estimated with the following formula:

$$\hat{d} = 1{,}000 \cdot \hat{f}(0) \cdot \hat{E}(s) \cdot ER / 2 \cdot$$

The “hats” over the letters designate estimates. An estimate of density for each PSU was constructed as a weighted average of the PSU subunit densities with the weights being the areas of the inshore and offshore subunits.

Estimates of Precision Within Strata

In general, bootstrap resampling methods were used to estimate precision. Because sampling logistics sometimes resulted in PSU samples that were clustered in time and space, estimating precision within a stratum required accounting for these clustered samples. Typically, surveys on the same day or within one day of each other and in adjacent PSUs, or within two PSUs, were considered clustered samples. To adjust for this clustering of PSU samples, we performed a bootstrap procedure where clusters were identified and randomly selected with replacement. Then, PSUs within each cluster were randomly selected with replacement. Both within stratum and within cluster resampling were used to produce one bootstrap replicate sample. The resulting bootstrap sample was then analyzed by the DISTANCE program, by using all the same methods as described in the preceding section.

Estimates of precision were based on 1,000 bootstrap replications (as described above). We used SAS (2000) to select the bootstrap replicate samples, run DISTANCE, calculate the density estimates, and summarize the bootstrap results.

Variants in Estimation Procedures

Estimation, as described in the previous two sections, varied slightly among most zones in some years. Some detection distances were not available in Zones 1 and 2 because of recorder malfunctions in the 2000 sample. Zone 5 had so few detections in all years that detection functions could not be calculated, so data for Zones 4 and 5 were combined to estimate values of $f(0)$ and $E(s)$.

Zone- and Population-Level Density Estimates

Once estimates of mean density and their associated estimates of precision were produced for each stratum, these stratum-level estimates were combined by using standard methods for stratified sampling. The methods, as described in Cochran (1977), involve proper weighting of stratum-level estimates by using the areas in each stratum. This produced estimates of mean density with associated estimates of precision for the target period for each zone, and for the entire target population consisting of all zones combined. Precision was estimated from the standard deviation of the results of the individual bootstrap iterations. Confidence intervals for density estimates were constructed from the central 95 percent of the bootstrap results (also known as the percentile method).

Construction of Confidence Intervals for Numbers of Birds

For each zone, we constructed a 95 percent confidence interval for the total number of birds by using the percentile confidence interval method (Efron 1992). For each of the 1,000 bootstrap replications, we estimated the number of birds in the zone by multiplying the estimate of density by the total area in the zone. These estimates were sorted from lowest to highest and the estimates ranked at the 25^{th} and 75^{th} percentiles were taken as the 95 percent confidence interval limits.

For the 95 percent confidence interval for the total number of birds in all zones combined, we calculated an estimate of the standard error and then added to and subtracted from the estimate of the total number of birds an amount 1.96 times that standard error to determine the confidence interval limits.

Estimates of target population change—
We used a regression model to determine if there was a change in the population from 2000 to 2003. Because the annual variances for each zone were approximately equal in the 4 years, and the error distributions of the bootstrap estimates appeared normal, the data met the regression model assumptions. Most often, the objective of monitoring species abundance is to detect a decrease over time. It is desirable to have the statistical power to detect a decline in a timeframe that allows managers to respond by altering the land management strategy. We elected, at this time, to test for a decrease in abundance over the monitoring period. We tested the hypothesis $H_0 : b = 0$ (no change in abundance) versus the hypothesis $H_1 : b < 0$ (abundance decreased) at the 5 percent significance level by fitting the following model to each of five zones and all zones combined:

$$= \quad + \qquad - \qquad + \varepsilon$$

a is the intercept, *b* is the slope, year = 2000, 2001, 2002, and 2003, and $\varepsilon \sim N(0, \sigma^2)$, where σ^2 combines the within- and among-year variability. This curve form describes a change that is linear over time on the log density scale, which corresponds to a proportional change in density over time. The percentage of change from one year to the next is $r = 100(e^b - 1)$. The intercept can be interpreted as the log of the density during 1999, and the slope is the relative change from one year to the next.

Estimating Power to Detect Trends in Population

In addition to identifying trends in population density, we wished to determine our power to detect a decline for all zones combined and for each zone. Our method for calculating power combines those described by Hogg and Craig (1995) and Draper and Smith (1998). If the log of annual estimate of density (*d*) for year *i* ($i = 1, 2, \ldots, n$) has a linear change over time with variance σ^2, then we write

$$y_i = \log_e(\hat{d}_i) = a + b \cdot i + \varepsilon_i$$

where $=$, $\hat{d}$ is the annual estimate of density, which is the mean number of birds per square mile at sea on any single day in the season (15 May through 31 July) and $\hat{d}_i$ is the estimate of density at year *i*, *a* is the intercept, ε_i is an error term with $\varepsilon_i \sim N(0, \sigma^2)$. The slope coefficient (*b*) is related to the annual percent change (*r*) as $r = 100(e^b - 1)$ or equivalently $b = \log_e(1 + \frac{r}{100})$. For example, if we were interested in a decrease of 5 percent per year, the value of *b* would be $=$.

The estimate for the slope, $\hat{b}$, has a variance given by the following:

$$\sigma^2_{\hat{b}} = \frac{\sigma^2}{\sum_{i=1}^{n}(i - \bar{i})^2} = \frac{12\sigma^2}{n(n-1)(n+1)}$$

The variance depends on both the variance of individual observations on a sample survey day (σ^2) and on the number of years of surveys.

If we want to perform the one-sided hypothesis test $H_0 : b = 0$ versus $H_1 : b < 0$, then we use

$$\text{Significance Level} = \alpha = \Pr\left(\frac{\hat{b} - 0}{\sqrt{\dfrac{12\hat{\sigma}^2}{n(n-1)(n+1)}}} < t_{n-2,\alpha} \mid b = 0 \right)$$

and

$$\text{Power} = 1 - \beta = \Pr\left(\frac{\hat{b} - 0}{\sqrt{\dfrac{12\hat{\sigma}^2}{n(n-1)(n+1)}}} < t_{n-2,\alpha} \mid b = b^* \right)$$

Note that $\dfrac{\hat{b}}{\sqrt{\dfrac{12\hat{\sigma}^2}{n(n-1)(n+1)}}}$ from above can be written as follows:

$$t = \frac{\hat{b}}{\sqrt{\dfrac{12\hat{\sigma}^2}{n(n-1)(n+1)}}}$$

$$= \frac{\hat{b}\sqrt{n(n-1)(n+1)/12}}{\sqrt{\hat{\sigma}^2}}$$

$$= \frac{\hat{b}\sqrt{n(n-1)(n+1)/(12\sigma^2)}}{\sqrt{\hat{\sigma}^2/\sigma^2}}$$

This statistic has a noncentral t-distribution with $n-2$ degrees of freedom and non-centrality parameter $\lambda = b^* \sqrt{n(n-1)(n+1)/(12\sigma^2)}$. Therefore, we determined the power by using routines that give the distribution of *t*.

Results

We have completed population-monitoring surveys in all conservation zones by using the above method for 4 consecutive years, beginning in 2000. Surveys have been conducted through the efforts, funding, and cooperation of federal and state governments, contractors, and private industry. The total target population offshore area for all zones is 3,393 mi^2 (8,788 km^2). We have conducted over 750 PSU surveys on approximately 15,984 mi (25,800 km) of transects, and recorded over 18,000 murrelet observations since 2000 (table 3-2).

Population Estimates

Estimates of density and population size by zone, stratum, and for all zones are presented by year in tables 3-3 through 3-6 and displayed for all years in figure 3-8. The total population estimate for the coastal waters adjacent to the Plan area for 2003, the most recent year, was 22,200 murrelets with a 95 percent confidence interval of 18,100 to 26,400 (table 3-3).

We estimated the highest densities of birds at the zone level over all 4 years in Zones 3 and 4, to be 12.24 and 10.90 birds per square mile (4.73 and 4.21 birds per km^2), respectively (tables 3-3 through 3-6). The highest annual zone densities were all observed in Zones 3 and 4. As expected, densities varied within zones with two- to eightfold differences between strata. Because of missing distance estimates in Zone 2 in 2000, we used the average *f(0)* over all 4 years to calculate density estimates. This may have contributed to the very low density estimate for Zone 2 in 2000. We observed the lowest densities of birds, 0.14 to 0.73 birds per square mile (0.05 to 0.28 birds per km^2), in Zone 5. We estimated the fewest birds in Zone 5: only 48 birds in 2003 (table 3-3) and 300 in 2002 (table 3-4).

Standard Error of Estimates

The estimated percent standard error of the population estimates is a measure of the variability in our sampling. This error of the density (tables 3-3 through 3-6) for all zones combined varied by year from 9.5 to 14.2. Zone 5, with its extremely low number of bird observations each year (from 7 to 58), and the many surveys with zero observations, produced the highest standard error each year for any of the zones.

Population Trends and Power Analysis

Estimates of target population change—

The goals of the Plan effectiveness monitoring approach for the marbled murrelet population are to estimate the size of the population and to identify trends over time. By the end of the 2003 survey season, we had 4 years of data collection and population estimates to begin to identify possible trends.

Our results did not detect a trend in the size of the target population over the 4 years of monitoring. None of the slopes for the five zones were significant at the 5 percent level (table 3-7, fig. 3-9).

The 95 percent confidence intervals for the annual percentage change in the population differ among the five zones. The largest confidence interval is in Zone 5, where we observed few birds and the estimate for the target population is very low. We consider the confidence intervals for the annual percentage change to be large for the 4 years of surveys (table 3-8), but not unexpectedly wide as the *t*-statistics used for the confidence intervals were based on only 2 degrees of freedom (and only 1 degree of freedom for Zone 2).

Power for detecting trends—

Our measure for assessing this monitoring program is its power to detect changes of interest in the mean density (and the resulting mean total population) of murrelets over time. Using the values for the mean square errors from the regressions (table 3-7) for each conservation zone and all zones combined, we estimated power to test the hypothesis

Table 3-2—The number of marbled murrelet population monitoring primary sampling unit (PSU) surveys completed for the Northwest Forest Plan each year by zone from 2000 through 2003 and the number of marbled murrelets observed

Year	Zone	Number of PSU surveys	Number of birds observed	Survey effort
				Miles
2000	1	54	437	1,056
	2	13	69	405
	3	24	701	623
	4	56	1,664	928
	5	29	25	492
2001	1	60	1,147	1,341
	2	22	250	646
	3	27	1,344	663
	4	55	1,116	883
	5	22	23	374
2002	1	60	1,631	1,387
	2	25	232	577
	3	31	1,425	770
	4	58	1,270	872
	5	26	58	438
2003	1	60	1,930	1,373
	2	30	475	854
	3	30	1,604	703
	4	56	1,775	881
	5	19	7	316
Totals		767	18,167	15,984

Table 3-3—Estimates of density[a] and target population size of marbled murrelets during the 2003 breeding season in the area of the Northwest Forest Plan

Zone	Stratum	Density	Bootstrap standard error	Standard error of the estimate	Birds[b]	Birds lower 95% CL[b]	Birds upper 95% CL[b]	Survey area	f(0)	Standard error of f(0)	E(s)	Standard error of E(s)	Truncation distance	Standard error of trunaction distance
		Birds/mi²		*Percent*				*Mi²*					*Feet*	
1	1	17.21	4.04	23.5	5,600	3,500	8,200	326						
1	2	3.73	1.21	32.4	1,700	900	2,800	461						
1	3	2.05	0.69	33.5	1,200	200	1,900	563						
1	All	6.29	1.12	17.9	8,500	5,700	11,700	1,351	0.003	0.0002	1.82	0.07	984	60.8
2	1	6.63	1.91	28.8	1,900	1,100	3,200	280						
2	2	4.08	1.51	37.1	1,500	500	2,400	358						
2	All	5.20	1.24	23.9	3,300	2,000	5,000	637	0.005	0.0006	1.40	0.08	262	18.2
3	1	3.09	0.72	23.4	800	500	1,200	255						
3	2	14.08	2.49	17.7	5,100	3,200	6,600	361						
3	All	9.52	1.55	16.2	5,900	3,900	7,600	616	0.004	0.0003	1.66	0.06	427	27.5
4	1	13.01	2.66	20.4	3,700	2,600	5,700	283						
4	2	4.92	1.38	27.9	800	600	1,500	164						
4	All	10.04	1.80	18.0	4,500	3,400	6,700	448	0.003	0.0002	1.71	0.05	584	27.8
5	1	0.28	0.18	63.8	48	0	100	170						
5	2	0	0	—	0	—	—	170						
5	All	0.14	0.09	63.8	48	0	100	341	0.003	0.0002	1.71	0.05	584	27.5
All	—	6.55	0.63	9.5	22,200	18,100	26,400	3,392						

[a] The probability of a bird being detected on the transect line (f(0)) and the mean number of birds per group (E(s)) were estimated by using DISTANCE software.

[b] Numbers rounded to the nearest 100 birds, if number was greater than 50. CL = confidence limits.

Table 3-4—Estimates of density[a] and target population size of marbled murrelets during the 2002 breeding season in the area of the Northwest Forest Plan

Zone	Stratum	Density	Bootstrap standard error	Standard error of the estimate	Birds[b]	Birds lower 95% CL[b]	Birds upper 95% CL[b]	Survey area	f(0)	Standard error of f(0)	E(s)	Standard error of E(s)	Truncation distance	Standard error of truncation distance
		Birds/mi²		*Percent*				*Mi²*					*Feet*	
1	1	18.63	6.23	33.4	6,100	2,800	10,000	326						
1	2	4.81	1.23	25.6	2,200	1,000	3,200	462						
1	3	2.51	0.78	31.0	1,400	600	2,400	562						
1	All	7.19	1.51	21.0	9,700	6,100	14,000	1,352	0.003	0.0003	1.76	0.07	636	27.2
2	1	8.11	2.72	33.5	2,300	400	3,500	280						
2	2	0.98	0.39	39.9	400	0	500	358						
2	All	4.11	1.26	30.6	2,600	600	3,800	637	0.006	0.0012	1.44	0.08	230	18.4
3	1	1.98	0.71	36.1	500	300	1,000	255						
3	2	15.98	3.79	23.7	5,800	3,500	9,200	361						
3	All	10.18	2.36	23.2	6,300	4,000	10,100	616	0.004	0.0008	1.93	0.12	492	37.5
4	1	13.52	1.97	14.6	3,800	2,600	5,000	283						
4	2	6.01	1.85	30.8	1,000	500	1,700	164						
4	All	10.76	1.48	13.8	4,800	3,600	6,200	448	0.003	0.0003	1.72	0.04	574	41.5
5	1	1.32	0.62	46.8	200	17	400	170						
5	2	0.14	0.10	71.6	24	0	100	170						
5	All	0.73	0.31	41.8	300	30	400	341	0.003	0.0003	1.72	0.04	574	41.5
All	—	6.98	0.80	11.5	23,700	18,300	29,000	3,393						

[a] The probability of a bird being detected on the transect line (f(0)) and the mean number of birds per group (E(s)) were estimated by using DISTANCE software.

[b] Numbers rounded to the nearest 100 birds, if number was greater than 50. CL = confidence limits.

Table 3-5—Estimates of density[a] and target population size of marbled murrelets during the 2001 breeding season in the area of the Northwest Forest Plan that were reanalyzed without using the hazard-rate function and using grouped perpendicular distances

Zone	Stratum	Density	Bootstrap standard error	Standard error of the estimate	Birds[b]	Birds lower 95% CL[b]	Birds upper 95% CL[b]	Survey area	f(0)	Standard error of f(0)	E(s)	Standard error of E(s)	Truncation distance	Standard error of truncation distance
		Birds/mi²		*Percent*				*Mi²*					*Feet*	
1	1	11.67	2.81	24.1	3,800	2,300	5,800	326						
1	2	4.57	0.94	20.6	2,100	1,000	2,800	462						
1	3	5.35	2.02	37.8	3,000	500	5,200	563						
1	All	6.61	1.26	19.0	8,900	5,500	12,600	1,352	0.004	0.0003	1.59	0.05	466	41.8
2	1	3.90	1.91	48.9	1,100	200	2,300	280						
2	2	1.81	1.99	110.2	600	100	2,400	358						
2	All	2.73	1.34	49.0	1,700	600	3,900	637	0.004	0.0012	1.47	0.28	262	18.6
3	1	4.52	1.12	24.8	1,200	600	1,700	255						
3	2	17.69	2.54	14.4	6,400	4,300	8,000	361						
3	All	12.24	1.65	13.5	7,500	5,300	9,300	616	0.005	0.0006	1.73	0.05	459	64.9
4	1	12.00	3.14	26.2	3,400	2,400	5,900	283						
4	2	2.74	0.84	30.6	500	300	900	164						
4	All	8.60	2.01	23.4	3,900	2,900	6,500	448	0.003	0.0002	1.75	0.07	558	22.1
5	1	0.43	0.18	40.9	100	7	100	170						
5	2	0.25	0.35	135.6	43	0	200	170						
5	All	0.34	0.20	57.8	100	14	300	341	0.003	0.0002	1.75	0.07	558	22.6
All	—	6.54	0.69	10.5	22,200	17,600	26,800	3,393						

[a] The probability of a bird being detected on the transect line (f(0)) and the mean number of birds per group (E(s)) were estimated by using DISTANCE software.

[b] Numbers rounded to the nearest 100 birds, if number was greater than 50. CL = confidence limits.

Table 3-6—Estimates of density[a] and target population size of marbled murrelets during the 2000 breeding season in the area of the Northwest Forest Plan that were reanalyzed without using the hazard-rate function and using grouped perpendicular distances

Zone	Stratum	Density	Bootstrap standard error	Standard error of the estimate	Birds[b]	Birds lower 95% CL[b]	Birds upper 95% CL[b]	Survey area	f(0)	Standard error of f(0)	E(s)	Standard error of E(s)	Truncation distance	Standard error of truncation distance
		Birds/mi²		*Percent*				*Mi²*					*Feet*	
1	1	8.71	2.17	24.9	2,800	1,600	4,200	326						
1	2	2.88	1.19	41.2	1,300	500	2,500	462						
1	3	2.60	1.52	58.4	1,500	100	3,100	563						
1	All	4.17	1.02	24.5	5,600	3,000	8,500	1,352	0.004	0.0004	1.53	0.08	587	39.6
2	1	3.18	1.19	37.4	900	400	1,700	280						
2	2	1.01	0.40	39.1	400	200	700	358						
2	All	1.96	0.62	31.6	1,300	700	2,200	637	0.005	0.0011	1.43	0.10	230	43.5
3	1	3.89	1.01	26.0	1,000	500	1,500	255						
3	2	15.89	4.06	25.6	5,700	3,200	8,700	361						
3	All	10.92	2.63	24.1	6,700	4,000	9,900	616	0.006	0.0010	1.64	0.11	279	21.7
4	1	15.58	5.24	33.6	4,400	3,000	8,700	283						
4	2	2.84	0.92	31.8	500	300	900	164						
4	All	10.90	3.35	30.1	4,900	3,500	9,300	448	0.003	0.0003	1.73	0.05	591	32.3
5	1	0.46	0.36	77.4	100	11	300	170						
5	2	0	0	—	0	—	—	170						
5	All	0.23	0.18	77.4	100	11	300	341	0.003	0.0003	1.73	0.05	591	32.3
All	—	5.47	0.78	14.2	18,600	13,400	23,700	3,393						

[a] The probability of a bird being detected on the transect line and the mean number of birds per group (E(s)) were estimated using DISTANCE software. Because zone 2 was sampled by using a fixed width transect in 2000, we used the average f(0) value from 2001 through 2003 to estimate density in this zone.

[b] Numbers rounded to the nearest 100 birds, if number was greater than 50. CL = confidence limits.

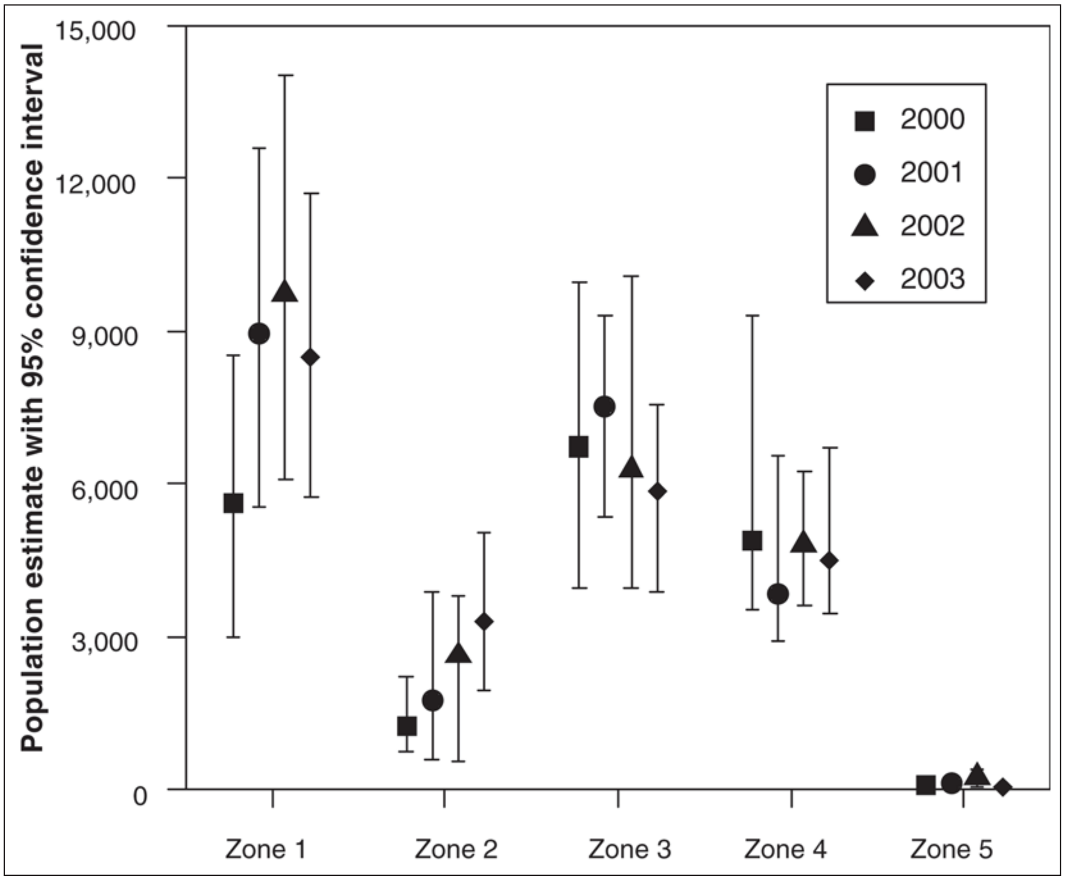

Figure 3-8—Marbled murrelet population estimates and 95 percent confidence intervals by zone and year in the area of the Northwest Forest Plan. In 2000, Zone 2 was sampled by using a fixed width transect; detection functions were not estimated for this zone, which resulted in a narrow estimate for the confidence interval.

Table 3-7—Estimates of the regression coefficients for trends in the target Northwest Forest Plan marbled murrelet population from 2000 to 2003

Zone	DF	Mean square error ($\hat{\sigma}^2$)	Intercept ($\hat{a}$)	se($\hat{a}$)	Estimated slope ($\hat{b}$)	se($\hat{b}$)	P-value for $H_0 : b = 0$
All	2	0.009	0.718	0.114	0.069	0.042	0.2393
1	2	0.044	0.502	0.257	0.131	0.094	0.2977
2	1	0.005	-0.606	0.149	0.333	0.048	0.0912
3	2	0.009	1.574	0.113	-0.059	0.041	0.2859
4	2	0.018	1.363	0.162	-0.003	0.059	0.9672
5	2	0.713	-1.971	1.034	-0.072	0.378	0.8664

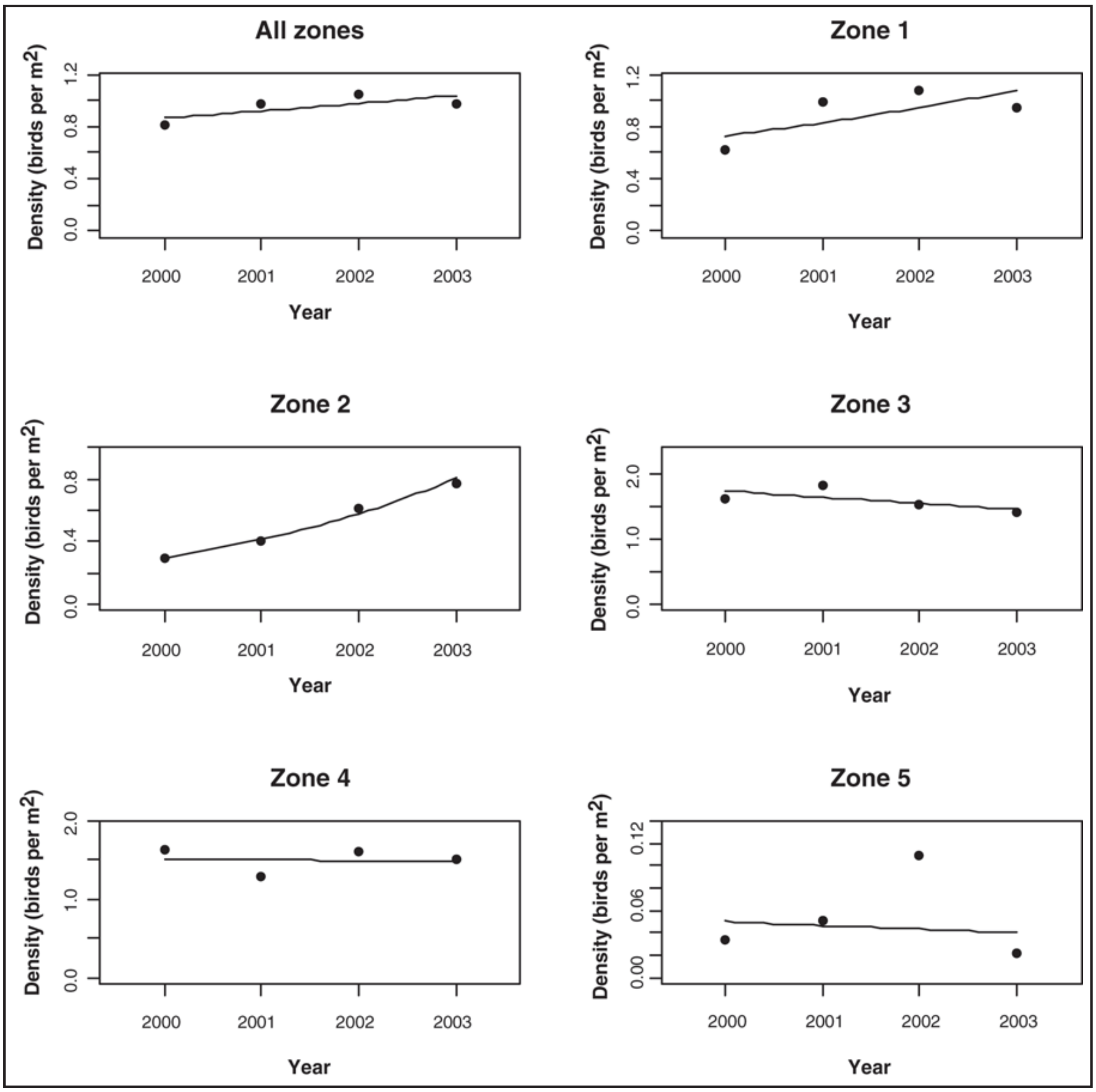

Figure 3-9—The observed densities and fitted curves for an analysis of trends from 2000 to 2003 in the target, Northwest Forest Plan marbled murrelet population.

Table 3-8—The estimates of annual percentage change from 2000 to 2003 and 95 percent confidence intervals in the Northwest Forest Plan target marbled murrelet population

Zone	Estimate of annual percentage change (r)	95% confidence interval Lower	Upper
All	7.1	-10.3	28.2
1	14.0	-23.8	70.8
2	39.5	-24.1	156.6
3	-5.7	-21.0	12.5
4	-0.2	-22.6	28.6
5	-6.8	-81.6	372.4

$H_0 : b = 0$ versus the hypothesis $H_1 : b < 0$ at the 5 percent significance level for various numbers of years for each zone. In figure 3-10 we present curves that estimate our power to detect various annual percentage decreases in density for 4, 5, 7, and 10 years. When all the zones are combined, we would have an 80 to 95 percent chance of detecting a 3- to 4-percent annual decrease with a 10-year sampling period. The decrease we could detect in 10 years, with 80 to 95 percent power, differs among the five zones (fig. 3-10, tables 3-9a and 3-9b). We have similar power to detect trends in Zones 2, 3, and 4. From the power analysis, we present a table of the number of years of survey required to detect from 2 to 10 percent annual declines in the murrelet populations in each zone and for all zones combined with 80 percent power (table 3-9a) and 95 percent power (table 3-9b). For all zones combined, in 15 years we could detect an annual decrease of 2 percent with 95 percent power. In only 10 years, we could detect a 3 percent annual decrease with 80 percent power.

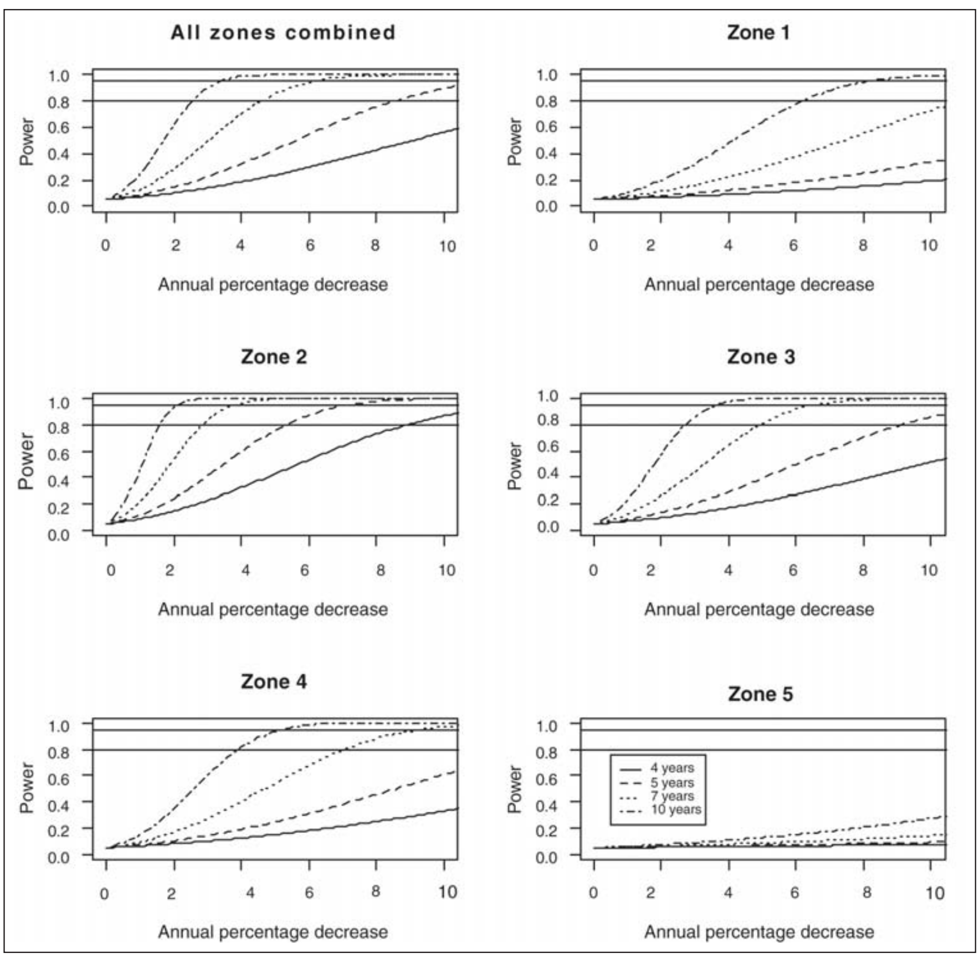

Figure 3-10—Power curves for detecting annual percentage of decreases in the Northwest Forest Plan marbled murrelet population for 4, 5, 7, and 10 years of surveys for each of the five zones alone and for all zones combined. Horizontal lines represent 80 percent and 95 percent power.

Table 3-9a—Estimate from the power analysis of the number of years of survey need to detect various percentages of annual decrease in the Northwest Forest Plan marbled murrelet population with 80 percent power or greater, in all conservation zones combined or by zone

Annual Decrease rate (%)	Zone					
	All	1	2	3	4	5
2	13	21	11	13	16	52
3	10	16	8	10	12	39
4	8	14	7	8	10	33
5	7	12	6	7	9	28
6	7	11	6	7	8	25
7	6	10	5	6	7	23
8	6	9	5	6	7	21
9	6	8	5	6	7	19
10	5	8	5	5	6	18

Table 3-9b—Estimate from the power analysis of the number of years of survey need to detect various percentages of annual decrease in the Northwest Forest Plan marbled murrelet population with 95 percent power or greater

Annual decrease rate (%)	Zone					
	All	1	2	3	4	5
2	15	25	12	15	19	62
3	12	19	10	12	15	47
4	10	16	8	10	12	39
5	9	14	7	9	11	34
6	8	13	7	8	10	30
7	7	11	6	7	9	27
8	7	11	6	7	8	25
9	6	10	6	6	8	23
10	6	9	5	6	7	21

Discussion

We anticipated an increase in density as chicks hatched and incubating birds returned to the water to forage with only short flights inland to feed chicks. However, examination of 2000 data did not suggest any temporal trends during our sampling season. This may be due to a variety of factors, including the proportion of birds breeding in any one year being small, or the return of breeders to the ocean whose nests failed during incubation. Our objective is to estimate the average number of birds in our target area between 15 May and 31 July, and to be able to detect trends in those estimates. Our sampling design will allow us to meet our objectives even if the number of birds on the water during the sampling period is not constant.

As we anticipated, few birds were observed in the offshore subunit. Most of our effort was in the inshore subunit, where densities were highest. Using this sampling design, we will continue to collect some samples in the offshore subunit and be able to detect and account for any shift in murrelet distribution, for instance, if the birds forage farther offshore in some years.

Our sampling design allows some flexibility in effort, by adjusting the number of surveys per year or the number of years of survey, to respond to changes in available funds. From 2000 to 2003, a population estimate was needed for Zone 4 stratum 2. Funds were contributed by one of the cooperators and additional surveys were conducted to complete 30 PSU samples in the stratum. By combining these surveys with all of the surveys in the zone, we were able to estimate populations at both the zone and stratum levels.

We met or exceeded target sample sizes for all zones except Zone 5, where the number of murrelets is extremely low. By reducing the number of samples in this zone, we have been able to continue to meet sampling effort in Zone 4, even though funding levels have dropped in the past 3 years. If we continue to conduct surveys in Zone 5 that are dispersed over the season, we should be able to detect large changes in the population in this area.

We acknowledge that our target population does not include the entire murrelet population in our zones. Some murrelets have been detected farther offshore in some zones (Ralph and Miller 1995, Raphael et al. 1999, Speich and Wahl 1995, Strong et al. 1995), particularly where bathymetric features reduce water depth. These studies indicate that only a small proportion of the population in our zones, generally less than 5 percent, is outside of our target population area, beyond 1.86 miles (3000 m) from shore. We feel that their numbers would have little effect on the total population estimates.

Marbled murrelet population estimates (summarized in chapter 2, this volume) have been published for all three states in the past decade (Miller et al. 2002, Peery et al. 2004, Ralph and Miller 1995, Raphael et al. 2002, Speich and Wahl 1995, Strong 2003, Strong et al. 1995, Varoujean and Williams 1995). Speich and Wahl (1995) based their estimates on bird counts during aerial surveys. Although methods for past offshore surveys from boats were similar to each other, some aspects of survey design and analytical methods differed among states and studies. In California and southern Oregon, line transect methods were used, with transects placed parallel to the shore along the entire coast at two distances that encompassed the peak densities of birds (Ralph and Miller 1995). On 20 percent of the surveyed coast, additional transects were placed out from shore at graduated intervals to 3 mi (5 km). A regression model describing the relationship between counts at the different distances was used to estimate the population size. Similar sampling designs were used in Oregon (Strong 2003, Strong et al. 1995), but transects were placed at different distances and modified strip transect methods were used to record observations. Population estimates from the sampling method for the Plan monitoring are not directly comparable to any of the earlier population estimates. Efforts are underway to compare estimates from past survey designs and analytical methods with estimates from the Northwest Forest Plan monitoring design. Simultaneous surveys and computer simulation techniques will be used. We expect that in the future, longer term trends can be examined.

Our power analysis addresses our ability to test for a decreasing linear trend in the target murrelet population adjacent to the Plan area. For all zones combined, we estimate in 7 years to be able to detect a 5 percent annual decline with 80 percent power. As we continue the effectiveness monitoring effort, the consequences of errors in estimating trends should be evaluated and goals established. In addition to setting population targets, management response to observed trends should be considered. Over the next few years, as the number of years of monitoring increases, we will be able to refine both our density estimates and our power to detect changes in the population at the Plan level and at the smaller zone level.

When you know:	Multiply by	To get:
Feet (ft)	0.305	Meter
Miles (mi)	1.609	Kilometers
Square miles (mi^2)	2.59	Square kilometers

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Chapter 4: Estimating the Amount of Marbled Murrelet Nesting Habitat on Federal Land by Using a Systematic Grid Sampling Strategy

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Abstract

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Our monitoring had two themes, presented as questions that apply to U.S. Forest Service and Bureau of Land Management lands in the Northwest Forest Plan (the Plan) area: (1) What is marbled murrelet nesting habitat? (2) What is the amount potential of nesting habitat at varying analysis scales? We used the survey location data to develop logistic regression equations to predict nesting sites that had habitat attributes similar to those of occupied sites. We used these equations to estimate odds ratios (transformed to a scale of -1 to 1) of inventory grid locations as nesting habitat based on vegetation and spatial data available for them, and estimated the amount of federal land in habitat suitability classes at the Plan, state, and physiographic province scales; by reserved and nonreserved land allocations; and by marbled murrelet inland management Zones 1 and 2.

Our experimental models predicted that murrelet occupancy is more likely at sites that are closer to the sea, are on relatively flat terrain, are topographically cooler, have relatively fewer conifers above pole size (≥10 in diameter at breast height [d.b.h.]), have greater basal area of trees above pole size, and that have greater basal area of larger-diameter trees (>30 in d.b.h.). We estimated that only 13 percent of U.S. Forest Service and Bureau of Land Management land had an even chance or better of being suitable nesting habitat; meaning that, the relative odds (odds ratios) were equal to or exceeded that of known occupied nesting habitat (i.e., the high suitability class). Washington had the highest proportion of federal land in the high suitability class for nesting, 7.4 percent; Oregon had 3.5 percent and California 4.8 percent. By physiographic province, the largest amount of high-suitability nesting habitat was in the Oregon Coast Range and Olympic Peninsula. Washington had the highest proportion of high suitability nesting habitat in federal reserves, 16.9 percent. To advance the largely experimental results of this study to broader applications, vegetation characteristics will need to be sampled at several hundred additional murrelet survey sites.

Introduction

The marbled murrelet (*Brachyramphus marmoratus*) is a small seabird that feeds along coastal waters and nests in forests with large trees up to 55 mi inland. Large tree branches (platforms), where marbled murrelets lay a single egg without constructing a nest, are one of the most important structural features of their nesting habitat (e.g., Hamer and Nelson 1995). From the late 1950s to the early 1990s, forests with large trees have declined rapidly

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throughout the Pacific Northwest, mostly from logging (FEMAT 1993). Because of habitat loss and other factors that can negatively affect persistence (e.g., oil spills, net fisheries, and nest predation), the marbled murrelet was listed federally as threatened in 1992 in the southern portion of its range: Washington, Oregon, and California (USDI FWS 1992, 1997). The ecology of the marbled murrelet is reviewed in Burger (2002), McShane et al. (2004), Nelson (1997), Nelson et al. (chapter 2, this volume), and Ralph et al. (1995).

In recovering the marbled murrelet from threatened status, the U.S. Fish and Wildlife Service relies on the Northwest Forest Plan (hereafter, the Plan) (FEMAT 1993; USDA and USDI 1994a, 1994b) as the "backbone" of its recovery strategy (USFWS 1997). The primary goal of the Plan is to maintain and restore late-successional and old-growth (older forest) habitat and ecosystems on federal lands (USDA and USDI 1994a, 1994b). Because of their strong association with late-successional and old-growth forests, the marbled murrelet and northern spotted owl (*Strix occidentalis caurina*) were singled out in the Plan for specific habitat management provisions and for additional research and monitoring.

The general strategy for monitoring environmental change and assessing the effectiveness of the Plan is in Mulder et al. (1999), which focuses on monitoring individual species and vegetation communities. Monitoring goals specific to marbled murrelet were developed by Madsen et al. (1999); these goals include identifying forest habitat conditions important for nesting, establishing a credible baseline for the amount and distribution of nesting habitat, and evaluating the effectiveness of the Plan relative to persistence of marbled murrelets. Specific objectives for this paper connected to the Plan goals are to (1) determine what habitat attributes are associated with nesting of marbled murrelets, and (2) estimate the amount of nesting habitat in the Plan area. By accomplishing these short-term objectives, changes and trends in the amount of potential nesting habitat and the effectiveness of the Plan can be assessed over time.

In the Plan, total nesting habitat of marbled murrelets[4] was estimated as 2.55 million acres on federal lands, including national parks (USDA and USDI 1994a: table 3 and 4-38, alternative 9: 3 and 4-222). Estimates of nesting habitat at the state, physiographic province, and land use allocation scales were provided in the Plan and were considered the best available information at the time (USDA and USDI 1994a: app. G: 25). However, the Plan estimates were derived mostly from interpretations of satellite imagery that lacked rigorous ground-truthing (USDA and USDI 1994a) and from broad ecological classifications of vegetation that were not habitat specific to marbled murrelets (Perry 1995). Two years later, potential nesting habitat estimates were released by the U.S. Fish and Wildlife Service when Critical Habitat was mapped for the "listed range" of the marbled murrelet; for federal land, those estimates were nearly identical to the protected allocations in the Plan (USFWS 1996). Since then, efforts to enhance these Planwide estimates have been hampered by incomplete and incompatible vegetation classifications across federal lands (McShane et al. 2004).

General understanding of marbled murrelet nesting habitat at the tree, site, and landscape scales has advanced considerably since the Plan was drafted (Nelson et al., chapter 2, this volume). Surveys from 1994 through 2001, yielded nearly 800 new locations where marbled murrelet nesting behavior was observed on federal and state lands (Raphael et al., chapter 5, this volume). Habitat data from a

[4] Suitable marbled murrelet nesting habitat is defined in the "Plan" as old-growth forests, and mature forests with an old-growth component of trees with >32 in diameter at breast height. Old-growth forest is defined as a forest stand usually at least 180 to 220 years old [dominant trees] with moderate to high canopy closure; a multilayered, multi-species canopy dominated by large overstory trees; high incidence of large trees, some with broken tops and other indications of old and decaying wood (decadence); numerous large snags; and heavy accumulations of wood, including large logs on the ground (FEMAT 1993).

broad base of new nesting locations studies revealed, for example, that marbled murrelets favor fog-associated, low-elevation old-growth forests in large unfragmented blocks near the marine environment for nesting and avoid nesting near forests with high-contrast edge in northern California and Oregon (Meyer et al. 2002, Meyer and Miller 2002, Ripple et al. 2003).

Recently, new vegetation data sources have become available (see Moeur et al. 2005) that provide new opportunities to estimate and monitor marbled murrelet nesting habitat on federal land. One source is a ground-based inventory of vegetation and other ecological characteristics on a systematic grid (Max et al. 1996). Compiled versions of the first-decade data from these inventories on federal land have been released through federal government Web sites, e.g., http://www.fs.fed.us/r6/survey/ and http://www.fs.fed.us/pnw/fia/. Large-scale systematic grid inventories have unique estimation potential, especially for fine-scale attributes that cannot be mapped accurately. They also have been used to train and validate spectrally interpreted classification of vegetation (see Moeur et al. 2005), thus enhancing efforts to revise maps of potential nesting habitat for marbled murrelets (Raphael et al., chapter 5, this volume).

Our objective was to develop a repeatable, effective, and efficient method for monitoring long-term changes in marbled murrelet nesting habitat. We organized this paper around two themes, presented as questions that apply to U.S Forest Service and Bureau of Land Management (BLM) lands in the Plan area: (1) What is marbled murrelet nesting habitat? (2) What is the amount of potential nesting habitat at varying analysis scales? Estimating amount of habitat is also an objective of chapter 5 (this volume). However, the methods and their potential utility to long-term monitoring of suitable nesting habitat differ between chapters: this chapter investigates uses of ground-based vegetation inventories remeasured at regular intervals, whereas chapter 5 investigates uses of interpreted satellite imagery.

Herein we present our predictions of the amount of nesting habitat obtained by coupling data from marbled murrelet survey locations and data from a systematic inventory grid that covers federal land in the Plan area. Our developmental (or training) data set was from plot-level vegetation measurements and spatial data from survey sites where marbled murrelets were sampled and either detected (exhibiting nesting behavior) or not detected (absent). We used those data to develop logistic regression equations to predict an optimal set of habitat variables associated with nesting. Adjusting our prediction equations to produce odds ratios[5] that are transformed to scale of -1 to 1, we estimated the transformed odds ratios of inventory grid locations as nesting habitat based on available vegetation and spatial data. We used the transformed odds ratios as a habitat suitability index. To estimate amount of nesting habitat for different geographic areas or allocations, we summed the area expansion represented by the grid points inventory plots within classes along the habitat suitability index. We reported these estimates at the Plan, state, and physiographic province scales; by reserved and nonreserved land allocations; and by marbled murrelet inland management Zones 1 and 2 (USDA and USDI 1994a), near and distant from coastline, respectively.

Methods

What Is Marbled Murrelet Nesting Habitat?

We used logistic regression, a linear modeling procedure that predicts dichotomous outcomes, to predict optimal sets of habitat variables for nesting. To accomplish this, we obtained data for our dependent variable from a random selection among a pool of sites surveyed to determine occupancy (occupied or absent) and for our predictor variables from the habitat attributes of the sites selected (i.e., case-controlled study design). Then, we developed equations that predicted the habitat attributes associated with nesting.

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[5] Odds ratio is the odds of an event occurring in one group compared to the odds of it occurring in another group, e.g., a control.

Data sources—

We used two types of data: (1) site occupancy—surveys that detect occupancy of marbled murrelets and (2) habitat—a set of environmental variables that describe the surveyed locations.

Site occupancy data—

Our site occupancy data were compiled and integrated from many existing data sources. We gathered information about marbled murrelet surveys that were conducted from 1994 to 2001 by government agencies in the Plan area. These surveys were performed by using a standardized protocol to determine site occupancy (Evans-Mack et al. 2003, Ralph et al. 1994), usually before proposed ground-disturbing projects or as part of research projects. A site consisted of 1 or more survey stations that were laid out together and which collectively were surveyed to determine the status of the site for marbled murrelets following this protocol. Occupancy was coded as either occupied: detected with nesting behavior (see Ralph et al. 1994); present: detected without nesting behavior; or absent: not detected. Only occupied and absent sites were used to make habitat predictions in this study. We assumed that sites surveyed by the agencies represented the breadth of possible marbled murrelet nesting habitat; however, the population of sites surveyed by the agencies were not selected randomly. From a pool of about 800 occupied and thousands of unoccupied sites, we randomly selected 200 sites, 20 occupied and 20 absent sites from each of the 5 major physiographic provinces that overlapped with murrelet Zones 1 and 2: Olympic Peninsula and Washington Cascades in Washington; Oregon Coast Range and Klamath Mountains in Oregon; and California Coast and Klamath Mountains provinces combined in California to collect plot-scale vegetation data. These data included the type of occupancy behavior, years surveyed, number of surveys, and number of surveys with occupancy. In developing our prediction model (see "Predicting Nesting Habitat Variables"), we removed 31 sites from the study because certain data attributes were not available from these sites to correct for inequitable detection effort among survey sites. Of the 169 sites used in our prediction model, 87 were occupied and 82 were absent (table 4-1 and fig. 4-1).

Site selection was not stratified between inland marbled murrelet Zones 1 and 2 (fig. 4-1). During our analysis, we discovered that none of the approximately 800 occupied sites in the selection pool were in Zone 2. Because of this finding, we developed two habitat prediction models: Zones 1 and 2 together (hereafter Plan Area model) and

Table 4-1—Number, status (occupied and absent), and province location of sites that were used to predict suitable nesting marbled murrelet habitat on federal land in the Plan area

Province	State	No. of occupied sites	No. of absent sites	Total
Olympic Peninsula	Washington	19	21	40
Western Cascades	Washington	11	14	25
Oregon Coast	Oregon	20	20	40
Klamath Mountains	Oregon	19	20	39
Klamath Mountains	California	—	4	4
California Coast	California	18	3	21
		87	82	169

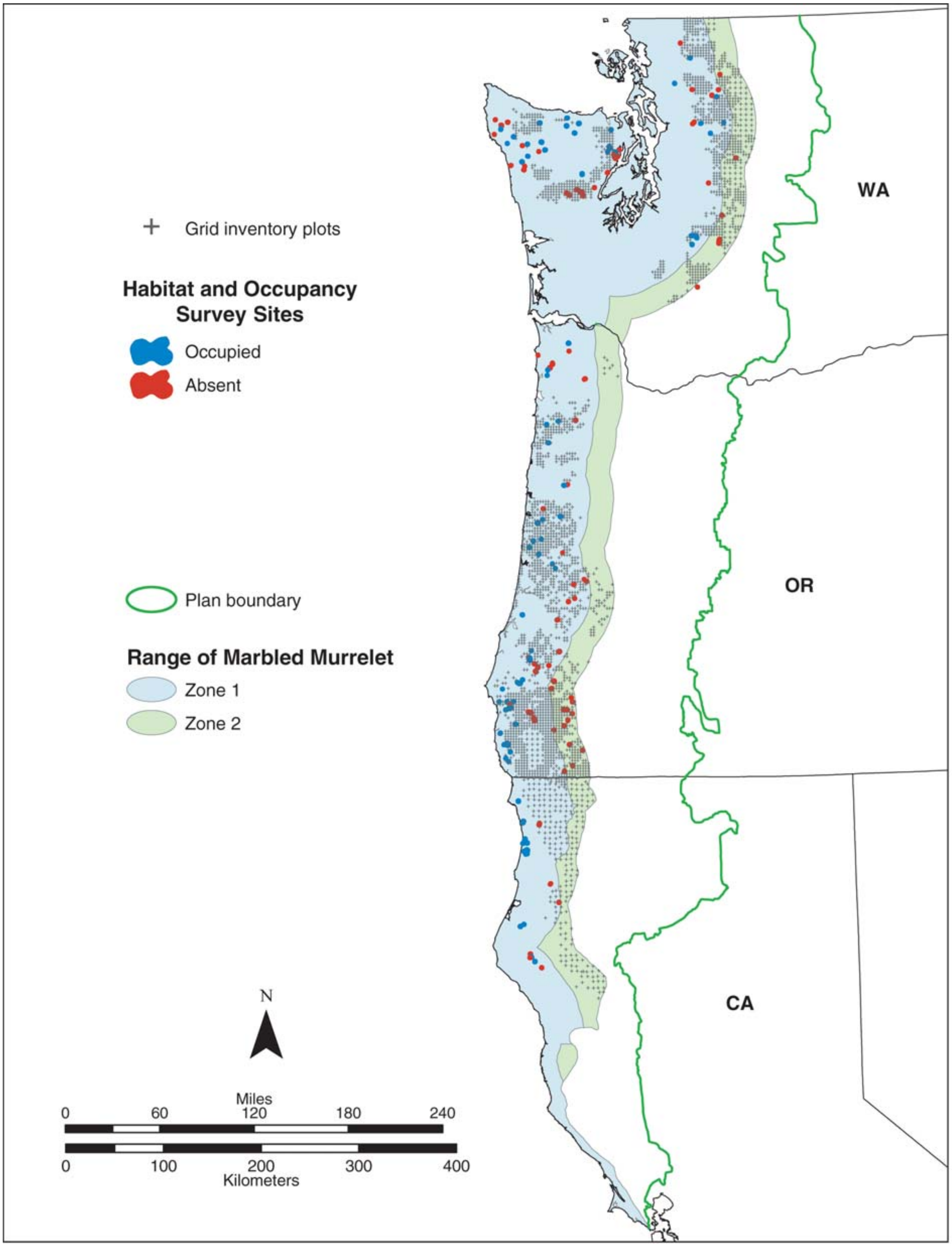

Figure 4-1—Northwest Forest Plan area, inland habitat Zones 1 and 2, distribution of marbled murrelet site occupancy surveys, and locations of systematic grid inventory plots.

Zone-1-Only. To develop our Zone-1-Only model, we removed the 20 sites in Zone 2 (13 from Oregon Klamath and 7 from Washington Western Cascades provinces).

We delineated boundaries of the "occupied" and "absent" sites by using maps and aerial photographs provided by the agencies doing the surveys. The boundaries often followed mature and older forest stands. The site boundaries and survey station locations were digitized into geographic information system (GIS) coverages. Digital raster graphics and digital orthophoto quads were used to geo-reference the digital site boundaries. Stand boundaries were adjusted further by removing large areas of unsuitable nesting habitat such as large waterways, river plains, large meadows, young forests (precanopy closure), two-lane paved roads, and power line cuts. If, in the process of removing the nonfunctional habitat, a site was subdivided into two or more unique polygons, only those polygons that contained survey sites for either birds or vegetation were retained. Polygons that lacked survey sites were removed from the site boundary data set.

Delineating site boundaries was done differently for survey sites from research projects where marbled murrelets were surveyed at stations along transects with no site boundaries. Using the research study areas of possible marbled murrelet nesting habitat as a base in GIS, we placed a 0.43-mi grid (120-acre cells) over the study area. Occupancy of each grid cell was determined by overlaying locations of prior occupancy surveys on the grid. A set of grid cells, occupied and absent, were selected randomly. To delineate outer site boundaries associated with each grid cell selected, a 0.27-mi-radius circle (150 acres) was centered over the cell and then boundaries were adjusted to follow stand edges. For all study sites, our initial goal for site size was about 5 to 150 acres; however, 27 sites (about 16 percent of our entire sample) were >150 acres, of which 12 (7 percent) were >175 acres.

Site habitat data—

For each of the 169 occupied and absent sites, we collected both on-the-ground, tree-scale vegetation data and remotely sensed, site-scale data. We sampled trees from 8 to 10 randomly located plots at each site. Each plot had an 82-ft radius, with a nested 43-ft-radius subplot. We sampled the entire plot for tree species and measured d.b.h. of trees >20 in, and in the subplot, trees 10 to 20 in d.b.h. In addition, we counted the number of platforms per tree, defined as branches ≥4 in diameter and ≥33 ft above the ground, in three basal branch diameter classes estimated from the ground: 4 to 6 in; >6 to 8 in; and >8 in, and two height classes estimated above the ground: 33 to 50 ft and >50 ft.

Spatial attributes for each site were quantified by using a combination of raster terrain models and GIS analysis techniques at 25-m (82-ft) pixel (grid) resolution. We calculated a mean and standard deviation of three attributes: elevation, slope, and solar radiation by using the Zonal Statistics function of the Spatial Analyst module of ArcMap 8.3.[6] All pixels in the site were used to calculate these values. Slope and elevation were derived from 30-m (98-ft) digital elevation models (DEMs) from the National Elevation Dataset. Solar radiation was calculated from one of three raster grids: western Washington, western Oregon, and northwestern California. Grids were created by using a public domain program, shortwavc.aml (found at http://www.wsl.ch/staff/niklaus.zimmermann/programs/aml1_2.html), enhanced by Jan Henderson and Greg Dillon.[7] That program calculates the maximum amount of shortwave radiation received at the surface of the earth for a given period accounting for slope, aspect, elevation, solar angle, length of daylight, and shading from nearby landforms. The input grids used are the 30-m DEMs. For each of the three state grids, a specific date was selected as input to the program to represent the midpoint of the marbled murrelet breeding season: June 19, 26, and 9 for Washington, Oregon, and California, respectively (dates interpreted from fig. 3 in Hamer and Nelson 1995).

[6] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

[7] Henderson, J.; Dillon, G. 2004. Personal communication. Area ecologist and spatial analyst, respectively, Olympic National Forest, 1835 Black Lake Blvd. SW, Olympia, WA 98152.

We also measured distance to coastline (marine water) as one of our predictor variables. This was measured from the geographic center of each site polygon to the nearest intersection along the coast, assuming a straight line from each site. The digital coastline information from Washington, Oregon, and California were modified by using Arc edit tools to close off major bays and rivers by digitizing a straight line between the two outermost points across the mouth of each bay or river. Because of its large size and distinct features, closing off the Columbia River was more complicated: a line was digitized due north from Clatsop spit to a point midway between East and West Sand Islands, and then due west to the southern tip of Cape Disappointment.[8]

Surrogate attributes of tree platforms—
Potential nesting platforms, defined as limbs >4 in diameter with epiphytes on the branch, are an important habitat factor. Platform-related data, however, are not routinely gathered in extensive forest inventories. We explored using tree diameter, a commonly measured tree and stand attribute, as a proxy to predict potential platform abundance (Raphael 2004) with logistic regression. We used our data for the occupied and absent sites in Washington state, where observers had counted potential platforms and measured diameters of 13,822 trees at 68 sites.[9] We found a strong relationship between tree diameter and the occurrence of potential platforms (fig. 4-2); however, it differed among tree species. Among all species, the probability of potential nesting platforms increased with tree diameter. Individual trees about 40 in d.b.h. had a 50 percent probability of having a platform (Raphael 2004). Potential platform density differed among stands, probably reflecting the mix of species present and occurrence of moss and dwarf mistletoe (*Areceuthobium* spp.). These initial findings indicate that large trees have more platforms and that tree diameter is a reasonable surrogate for platform availability for our study; however, other examinations have not shown as strong a relationship as Raphael observed (see Nelson et al., chapter 2, this volume).

Habitat variables—
We preselected eight habitat variables, four derived from the occupied and absent site vegetation plots and four from GIS queries, to characterize marbled murrelet habitat by using logistic regression (table 4-2). Density and basal area of trees >30 in d.b.h. were selected as habitat variables based on relationships examined above. In the habitat database, each variable had one value for each of the 169 (occupied or absent) sites. Each variable was expressed as a sample mean calculated from plot and pixel data averaged for each site (except distance to coastline).

Summary statistics of the eight habitat variables for absent and occupied sites are shown in table 4-3 in columns 1 and 2, for the Plan area by state. In general, the absent sites were farther from the coast in Washington, Oregon, and California; the absent and occupied sites differed among states for the other variables. We did not test differences between occupied and absent sites statistically because our goal was to identify the subset of variables that had the best predictive ability of marbled murrelet habitat; thus, it is not necessary or expected that all the habitat data sets in consideration be significantly different, or uniform.

None of the habitat variable means had large differences between occupied and unoccupied sites except BA10 and BA30 (basal area of trees >10 in and >30 in d.b.h.), which were highly correlated (table 4-4). Both basal area variables had similar means and standard deviations for Oregon and Washington, which differed from California (fig. 4-3; BA30 shown only) because of differences in tree species and size. We concluded that a model that does not account for these differences is likely to produce unreliable results. Because of this, we used two variables associated with BA30, each allowed to enter the variable selection process: (1) BA30Low—values of BA30 below basal area

[8] Strong, C. 2004. Personal communication. Marine avian ecologist, Crescent Coastal Research, P.O. Box 2108, Crescent City, CA 95531.

[9] Data on file with: M. Raphael, USDA Forest Service, Forestry Sciences Laboratory, Olympia, WA; 98512.

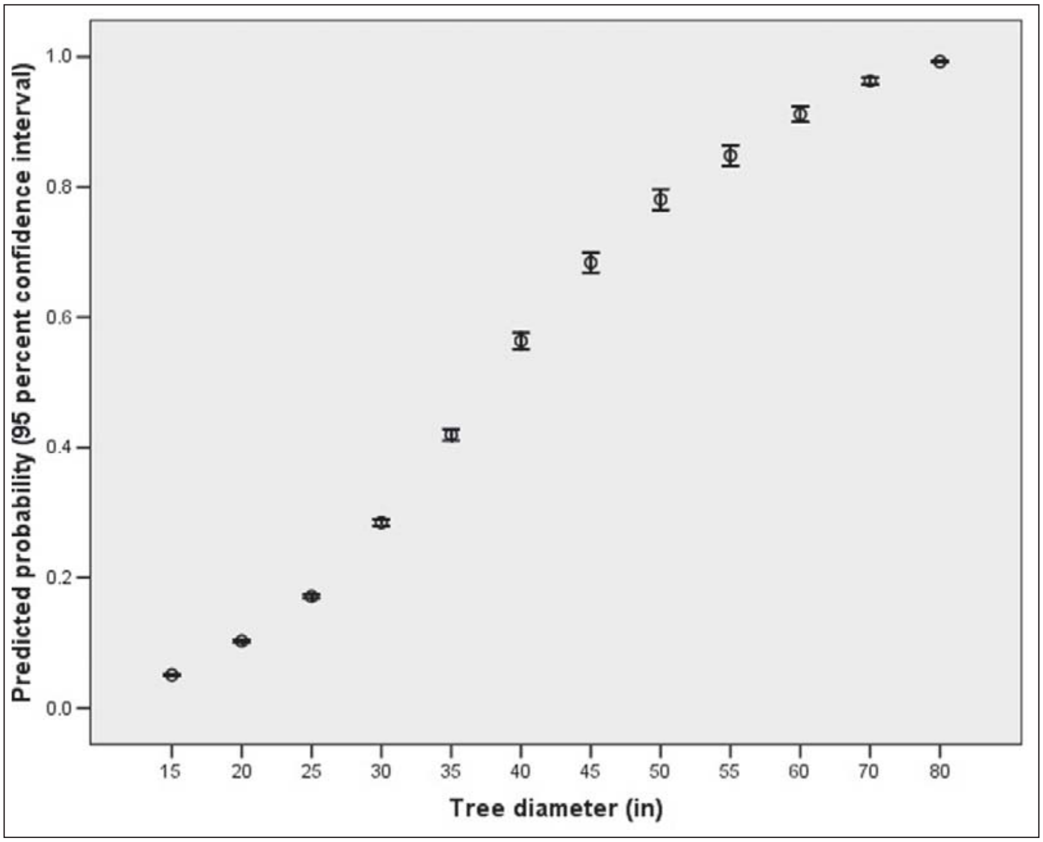

Figure 4-2—Predicted probabilities and 95 percent confidence intervals of platform branch occurrence by tree diameter for all tree species.

Table 4-2—Variables selected to develop a prediction equation of suitable marbled murrelet nesting habitat by using logistic regression

Variable type	Variable name and data type (plot or GIS)	Units
Mean density of conifer stems >10 in d.b.h.[a]	CDEN10 (plot)	No./ac
Mean number of conifer stems >30 in d.b.h	CDEN30 (plot)	No./ac
Mean conifer basal area trees >10 in d.b.h.	BA10 (plot)	ft^2/ac
Mean conifer basal area trees >30 in d.b.h.	BA30[b] (plot)	ft^2/ac
Mean solar radiation index	SRIM (GIS[c])	Index
Distance to coastline	SEADIST (GIS)	Miles
Mean elevation	ELEVM (GIS)	Feet
Mean slope	SLOPEM (GIS)	Percent

[a] d.b.h = diameter at breast height.

[b] BA30 is split into two "indicator" variables: (1) BA30Low—values of BA30 below basal area of 100 m^2/ha (436 ft^2/acre), otherwise zero and (2) BA30High—values of BA30 at or above 100 m^2/ha, otherwise zero.

[c] GIS = geographic information system.

Table 4-3—Habitat variables compared by state and by two data sources: (1) occupancy from marbled murrelet surveys and (2) odds ratios (untransformed) predicted from grid inventory data

			Occupancy surveys		Grid inventory	
	State	Statistic	Absent	Occupied	Odds ratio <1	Odds ratio ≥1
Distance to salt water (miles)	California	Mean	18.1	6.3	22.6	20.8
		Median	18.1	3.5	23.1	22.7
		Std. dev.	5.6	6.3	7.8	6.6
		N	7	18	95	13
	Oregon	Mean	30.8	11.3	20.7	13.1
		Median	33.7	8.5	21.0	12.3
		Std. dev.	12.4	6.4	10.1	8.3
		N	40	39	1,107	141
	Washington	Mean	19.7	17.0	24.9	18.3
		Median	13.9	13.6	27.0	16.2
		Std. dev.	16.8	11.7	11.3	11.4
		N	35	30	574	97
	All	Mean	25.0	12.2	22.2	15.5
		Median	23.3	8.7	22.9	13.4
		Std. dev.	15.1	9.4	10.6	9.9
		N	82	87	1,776	251
Mean slope (%)	California	Mean	20.8	16.1	22.5	32.3
		Median	17.4	16.3	22.3	33.3
		Std. dev.	8.1	2.8	7.4	3.8
		N	7	18	95	13
	Oregon	Mean	20.5	21.1	20.4	24.2
		Median	21.0	19.9	20.2	26.4
		Std. dev.	5.4	4.9	8.0	9.6
		N	40	39	1,107	141
	Washington	Mean	18.0	16.3	23.6	29.8
		Median	14.2	13.8	24.6	29.9
		Std. dev.	8.4	8.2	10.8	8.5
		N	35	30	574	97
	All	Mean	19.5	18.4	21.5	26.8
		Median	20.2	17.6	21.7	27.9
		Std. dev.	7.1	6.4	9.1	9.4
		N	82	87	1,776	251
Mean solar radiation index	California	Mean	26,912	27,974	26,934	22,461
		Median	27,054	27,809	27,016	22,323
		Std. dev.	1,938	417	1,479	1,257
		N	7	18	95	13
	Oregon	Mean	26,998	27,052	27,391	24,565
		Median	27,203	27,092	27,760	24,271
		Std. dev.	1,453	1,257	1,597	2,471
		N	40	39	1,107	141
	Washington	Mean	27,273	26,387	26,495	21,767
		Median	27,552	26,433	27,014	22,211
		Std. dev.	1,428	1,662	2,197	2,686
		N	35	30	574	97
	All	Mean	27,108	27,014	27,077	23,375
		Median	27,400	27,378	27,501	23,424
		Std. dev.	1,474	1,412	1,853	2,848
		N	82	87	1,776	251

Table 4-3—Habitat variables compared by state and by two data sources: (1) occupancy from marbled murrelet surveys and (2) odds ratios (untransformed) predicted from grid inventory data (continued)

			Occupancy surveys		Grid inventory	
	State	Statistic	Absent	Occupied	Odds ratio <1	Odds ratio ≥1
Density of conifers >10 in d.b.h. (No./acre)	California	Mean	38.9	44.7	37.7	30.3
		Median	41.8	44.5	29.8	31.9
		Std. dev.	10.5	7.5	31.9	17.7
		N	7	18	95	13
	Oregon	Mean	69.0	52.8	51.2	30.3
		Median	61.0	46.8	40.2	27.9
		Std. dev.	34.1	29.9	43.3	23.3
		N	40	39	1,107	141
	Washington	Mean	88.2	71.0	74.8	42.0
		Median	81.8	67.6	68.9	38.7
		Std. dev.	29.0	19.9	55.4	35.7
		N	35	30	574	97
	All	Mean	74.6	57.4	58.1	34.8
		Median	68.4	53.5	48.1	31.3
		Std. dev.	33.5	25.4	48.5	29.0
		N	82	87	1,776	251
Basal area of conifers >10 in d.b.h. (ft^2/acre)	California	Mean	371.0	961.9	94.9	146.2
		Median	281.0	977.8	69.0	153.7
		Std. dev.	220.9	358.1	91.5	100.5
		N	7	18	95	13
	Oregon	Mean	254.0	248.0	123.1	149.5
		Median	250.7	217.9	106.0	134.7
		Std. dev.	101.5	111.1	99.5	113.8
		N	40	39	1,107	141
	Washington	Mean	231.8	266.1	148.4	131.9
		Median	217.6	261.1	142.2	125.2
		Std. dev.	66.3	72.6	113.3	113.0
		N	35	30	574	97
	All	Mean	254.5	401.9	129.8	142.5
		Median	238.8	263.4	113.6	134.7
		Std. dev.	108.7	339.7	104.7	112.8
		N	82	87	1,776	251
Basal area of conifers >30 in d.b.h. for sites with basal area ≤436 ft^2/acre	California	Mean	96.9	12.0	44.2	111.3
		Median	52.9	.0	8.9	105.6
		Std. dev.	109.4	51.0	63.3	98.7
		N	7	18	95	13
	Oregon	Mean	140.2	147.5	54.1	108.8
		Median	133.3	136.7	18.2	87.1
		Std. dev.	94.9	88.5	73.4	95.2
		N	40	39	1,107	141
	Washington	Mean	97.0	159.8	50.1	76.2
		Median	83.3	136.7	12.6	56.3
		Std. dev.	66.7	87.1	71.4	78.3
		N	35	30	574	97
	All	Mean	118.1	123.7	52.3	96.3
		Median	94.7	117.5	16.8	78.8
		Std. dev.	86.9	99.3	72.3	90.3
		N	82	87	1,776	251

Table 4-3—Habitat variables compared by state and by two data sources: (1) occupancy from marbled murrelet surveys and (2) odds ratios (untransformed) predicted from grid inventory data (continued)

			Occupancy surveys		Grid inventory	
	State	**Statistic**	**Absent**	**Occupied**	**Odds ratio <1**	**Odds ratio ≥1**
Basal area of conifers >30 in d.b.h. for sites with basal area ≥436 ft^2/acre	California	Mean	233.0	911.7	.0	.0
		Median	.0	926.2	.0	.0
		Std. dev.	298.8	388.4	.0	.0
		N	7	18	95	13
	Oregon	Mean	13.2	26.2	.5	.0
		Median	.0	.0	.0	.0
		Std. dev.	83.8	114.7	16.5	.0
		N	40	39	1,107	141
	Washington	Mean	.0	.0	.8	.0
		Median	.0	.0	.0	.0
		Std. dev.	.0	.0	18.9	.0
		N	35	30	574	97
	All	Mean	26.4	200.4	.6	.0
		Median	.0	.0	.0	.0
		Std. dev.	118.6	411.4	16.9	.0
		N	82	87	1,776	251

Table 4-4—Correlations among habitat variables by using the survey location data and by grid location data

	Distance to coastline	Slope	Solar radiation index	Density of conifers >10 in d.b.h	Basal area of conifers >10 in d.b.h	BA30LOW: low range of conifer basal area for trees >30 in d.b.h.	BA30HIGH: high range of conifer basal area for trees >30 in d.b.h.
Survey location data							
Distance to coastline	1	.068	-.221**	-.030	-.254**	.237**	-.275**
Slope	.068	1	-.630**	-.108	-.150	.132	-.141
Solar radiation index	-.221**	-.630**	1	.093	.279**	-.073	.243**
Density of conifers >10 in d.b.h.	-.030	-.108	.093	1	-.121	-.163*	-.223**
Basal area of conifers >10 in d.b.h.	-.254**	-.150	.279**	-.121	1	-.260**	.957**
BA30LOW: low range of conifer basal area for trees >30 in d.b.h.	.237**	.132	-.073	-.163*	-.260**	1	-.476**
BA30HIGH: high range of conifer basal area for trees >30 in d.b.h.	-.275**	-.141	.243**	-.223**	.957**	-.476**	1
Grid location data							
Distance to coastline	1	.060**	-.059**	.036	.011	-.035	.008
Slope	.060**	1	-.654**	-.015	.060**	.070**	.016
Solar radiation index	-.059**	-.654**	1	.053**	-.004	-.046*	.010
Density of conifers >10 in d.b.h.	.036	-.015	.053**	1	.645**	.075**	.009
Basal area of conifers >10 cm d.b.h.	.011	.060**	-.004	.645**	1	.760**	.110**
BA30LOW: low range of conifer basal area for trees >30 in d.b.h.	-.035	.070**	-.046*	.075**	.760**	1	-.020
BA30HIGH: high range of conifer basal area for trees >30 in d.b.h.	.008	.016	.010	.009	.110**	-.020	1

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

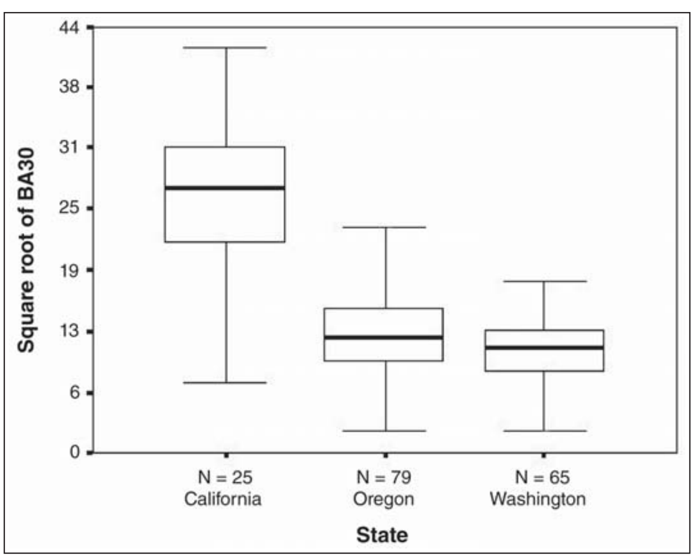

Figure 4-3—Box and whisker plot square-root-transformed BA30, basal area (ft^2/ac) of trees >30 in diameter at breast height, by state. The dark line is in the median; the box represents the interquartile range of 25th to 75th percentiles; whiskers extended out to highest and lowest values.

of 100 m^2/ha (436 ft^2/acre) otherwise zero and (2) BA30High—values of BA30 at or above 100 m^2/ha, otherwise zero. With a break point of 100 m^2/ha, most Washington and Oregon sites were exclusively in BA30 Low (fig. 4-3; below about 21 ft^2/acre). The effect of separating data above and below a threshold is that two separate slopes will be applied to estimate the amount of potential habitat.

Predicting nesting habitat variables—
Our intent was to project the probability of a potential marbled murrelet nesting site as either occupied or absent by using an optimal set of (predictor) variables selected from habitat data collected at marbled murrelet survey sites (sensu Trexler and Travis 1993). Our use of logistic regression did not require probabilistic distributions of the independent variables, but did require that ranges of the independent variables match what is found in the overall population. In theory, our dependent variable in the logistic regression model should have a value of one when a site is occupied by marbled murrelets, and zero when they are absent. However, the probability of detecting marbled murrelet occupied behavior, if it occurs, is less than one. We accounted for this by modifying standard logistic regression equations for (1) number of visits (inequitable detection effort), (2) number of visits with occupied detections (inequitable detections), and (3) site size (inequitable detection rate owing to scale), according to methods in MacKenzie et al. (2002). The adjustments were done by using a maximum likelihood approach available in program PRESENCE found at Web site http://www.proteus.co.nz. Adjustments were made by state because of differences in survey protocols from 1994 to 2001 and vegetation characteristics.

We developed two prediction models, Plan Area and Zone-1-Only. The Plan Area model predicts occupancy of marbled murrelet on U.S. Forest Service land in Washington, Oregon, and California and BLM land in Oregon in Zones 1 and 2 (hereafter, Plan area). We developed a separate model for Zone-1-Only because all "occupied" sites from 1994 to 2001 were in Zone 1. To develop the Zone-1-Only model, we removed the absent site data (20 total) that were in Zone 2; otherwise, the methods between models are identical. We used four general steps in building each model:

1. We selected 30 candidate models of all possible sets of predictor (habitat) variables by using a scoring statistic (The scoring statistic is a chi-square statistic used by SAS[10] in its LOGISTIC procedure, and the only summary statistic currently available for all-possible subsets; predictor variables are listed in table 4-2).
2. We performed an adjustment for the lack of perfect detection on each of the top models.
3. We used Akaike Information Criterion (AICc) (Burnham and Anderson 2002) to rank the top candidate models, and selected the model with the smallest AICc value as our predictor model. AICc provides a relative ranking and does not give an absolute goodness-of-fit measure. The quality of the model was assessed by the "confusion matrix" containing the number of times that the predictions matched the observed data based on using a predicted probability of greater than 0.5 as indicating occupancy and less than or equal to 0.5 indicating lack of occupancy.
4. We ranked predictor variables based on the change in AICc when each variable was removed individually from the top models. The relative importance of individual predictor variables was assessed based on the loss of predictive capabilities as each was removed.

What Is the Amount of Potential Nesting Habitat?

To estimate amounts of potential nesting habitat, we first predicted the relative suitability of forest inventory grid locations as nesting habitat by computing odds ratios and then multiplied by the area represented by that grid location.

[10] SAS software is a product with registered trademarks of SAS Institute Inc., Cary, NC.

Data sources—

We used three types of data to estimate the amount of nesting habitat: (1) large-scale forest inventories (collected with a systematic grid design) managed by the U.S. Forest Service and BLM, (2) area expansion for inventory grid points, and (3) spatial layers to define geographic areas.

Systematic inventory grid data—

Agency inventory grid plot data were provided from three sources through the Effectiveness Monitoring Program (see Moeur et al. 2005): (1) Current Vegetation Survey (CVS) data from the U.S. Forest Service, Pacific Northwest Region, (2) CVS data from the BLM, and (3) forest inventory data from U.S. Forest Service, Pacific Southwest Region, as measured by the Forest Inventory and Analysis Unit of the Pacific Northwest Research Station. We used only plot data measured on land managed by the U.S. Forest Service and by the BLM. Grid inventory plots were not installed on lands managed by the USDI National Park Service or by the BLM in California. We used the first measurements of the grid inventories, which span 1993 to 1997; these measurements were considered a sample of the Plan area from the start of the Plan (1994) regardless of the year they were measured (Moeur et al. 2005).

Field methods for the grid inventories are found at http://www.fs.fed.us/r6/survey/ and http://www.fs.fed.us/pnw/fia/. There are minor differences in methods between agencies and between California and Washington and Oregon; however, they do not affect analyses in this paper. The primary sample unit (PSU) is a 1-ha (2.47-ac) circle, with five nested subplots, where vegetation and other ecological characteristics were sampled. Inventory data were at the PSU-subplot scale (usually five subplots, occasionally 1 to 4), so we averaged the subplots for a single PSU value.

Of the comprehensive ecological information that was collected during the grid inventories, only that which is shown in table 4-2 applies to this study. Data on tree branch platforms were collected in these broad-scale inventories on a subset of plots; however, sample size was deemed insufficient for use in this study. The spatial variables that are shown in table 4-2 were measured for each grid point location by using the methods described above in "Predicting Nesting Habitat." In doing this, we assumed that a PSU for the grid inventory, although much smaller in size, was analogous to our site occupancy polygons that were surveyed for marbled murrelets. Then, we used the plot center of each PSU to measure distance to coastline and calculated the mean and standard deviation of spatial variables by using data accessed from a 3 x 3, 9-pixel window (90 x 90 m) [295 x 295 ft] draped over each PSU.

Area expansion factors—

The PSUs are a collection of samples from grid locations that we used to estimate the amount of potential nesting habitat. Each PSU in the grid was assumed to "contribute" a certain amount of land area to the total area studied, and was not necessarily representative of the local area from where the sample was taken (i.e., samples do not have fine-scale predictive information). The federal land area contributed by each PSU was calculated separately for each national forest and BLM district by determining the area in each "management unit" and dividing by the number of PSUs. The grid inventory on federal land was not always the same density (e.g., wilderness areas had a sparser grid than other areas); if this density variation occurred within a management unit, area expansions were calculated separately. These data, reported as acres represented by each subplot within each PSU, were provided by the U.S. Forest Service and BLM and are described further by Moeur et al. (2005). To make projections at the PSU scale, we summed the acreages among subplots for each PSU.

Spatial layers—

We used three spatial layers to define the various geographic areas and land use allocations to estimate amount of potential nesting habitat: the marbled murrelet potential range and inland zones, physiographic province, and land use allocation. The digital map of the marbled murrelet's "potential range"[11] was used to define the study area extent. Only those PSU grid locations that fell within this boundary were used for this effort. It also maps two zones: near (Zone 1) and distant (Zone 2) from coastline. Zone 1 corresponds to the primary inland nesting range of marbled murrelet extending about 40 mi inland in Washington, 35 mi inland in Oregon, 25 mi inland in California north of Fort Bragg, and 10 mi inland south of Fort Bragg; Zone 2 accommodates irregular inland marbled murrelet sightings east of Zone 1, covering up to about 50 mi from the coastline (Madsen et al. 1999, USDA and USDI 1994a).

The physiographic province map delineated the boundaries of the Plan and the 12 physiographic provinces that overlap the Plan area. The coastline in the original marbled murrelet potential range map was rudimentary and was updated by using the higher resolution physiographic province layer, without changing the extent of the marbled murrelet inland zone boundaries.

The land use allocation layer, created specifically for the Plan, included land types that we grouped as (1) reserved: congressionally reserved, late-successional reserves, adaptive management areas in reserves, managed late-successional areas, administratively withdrawn, marbled murrelet reserve areas, and spotted owl core areas; and (2) nonreserved: matrix, and adaptive management areas (types defined in USDA and USDI 1994a). Reserved and nonreserved groups are mapped for the Plan area in fig. 4-4. A land use allocation type called riparian reserve, a buffer that overlies riparian ecosystems, was not mapped in the Plan and subsequent land use allocation layer revisions, and therefore this type was not included in our analyses. The 1994 (Plan) land use allocation map had many inaccuracies, most related to the map's coarse scale (40-acre resolution). Most problems have been corrected in the revised version used for this study; however, some inaccuracies, although minor in scope, exist in the revised layer and are described in Lint (2005).

[11] The "Potential Range of the marbled murrelet" was designated by the Forest Ecosystem Management Assessment Team in 1993 to identify the land area within the Plan in which the marbled murrelet is likely to nest. Since 1993, some local refinements to this range have been made for management purposes (e.g., where to survey), but they are not official changes to the Plan-designated range and therefore are not displayed.

Data analyses—

Logistic regression often is misapplied in the habitat modeling literature, especially when making predictions from case-controlled study designs, according to Keating and Cherry (2004) who recently reexamined the use and interpretation of logistic regression in habitat-selection models. To approximate unbiased estimates, they recommend calculating odds ratios, rather than probabilities for such studies.

Our area-based projections were based on two factors, occupancy odds ratios and expansion factor of grid inventory plots (PSUs). We calculated the odds ratios for each of the 2,765 (PSU) inventory grid locations by using the logistic regression habitat variables shown in table 4-2 compared to a reference condition. Our reference was the average habitat conditions of the 87 occupied sites (see table 4-3). Inventory grid locations with odds ratios of <1, 1, or >1 had lower, equivalent, or higher odds of being suitable nesting habitat relative to average habitat conditions of occupied sites. We set the projected occupancy odds to zero if the PSU elevation exceeded the limits in table 4-5 (after Raphael et al., chapter 5, this volume) or the PSU location was not capable of being forested (e.g., rock outcrop). Our calculations of odds ratios followed Keating and Cherry 2004 and Hosmer and Lemeshow 1989.

We use the odds ratio calculated for each PSU, which is an index of "potential nesting habitat," given that PSU locations were not surveyed for occupancy. However, occupancy by marbled murrelets depends not just on available nesting habitat, but numerous other factors, most notably total population size, which undoubtedly is influenced by factors unrelated to nesting habitat (e.g., conditions at sea). The area of influence of individual PSUs for these methods is the geographic area from which the PSUs were selected, and not necessarily the immediate area surrounding each PSU.

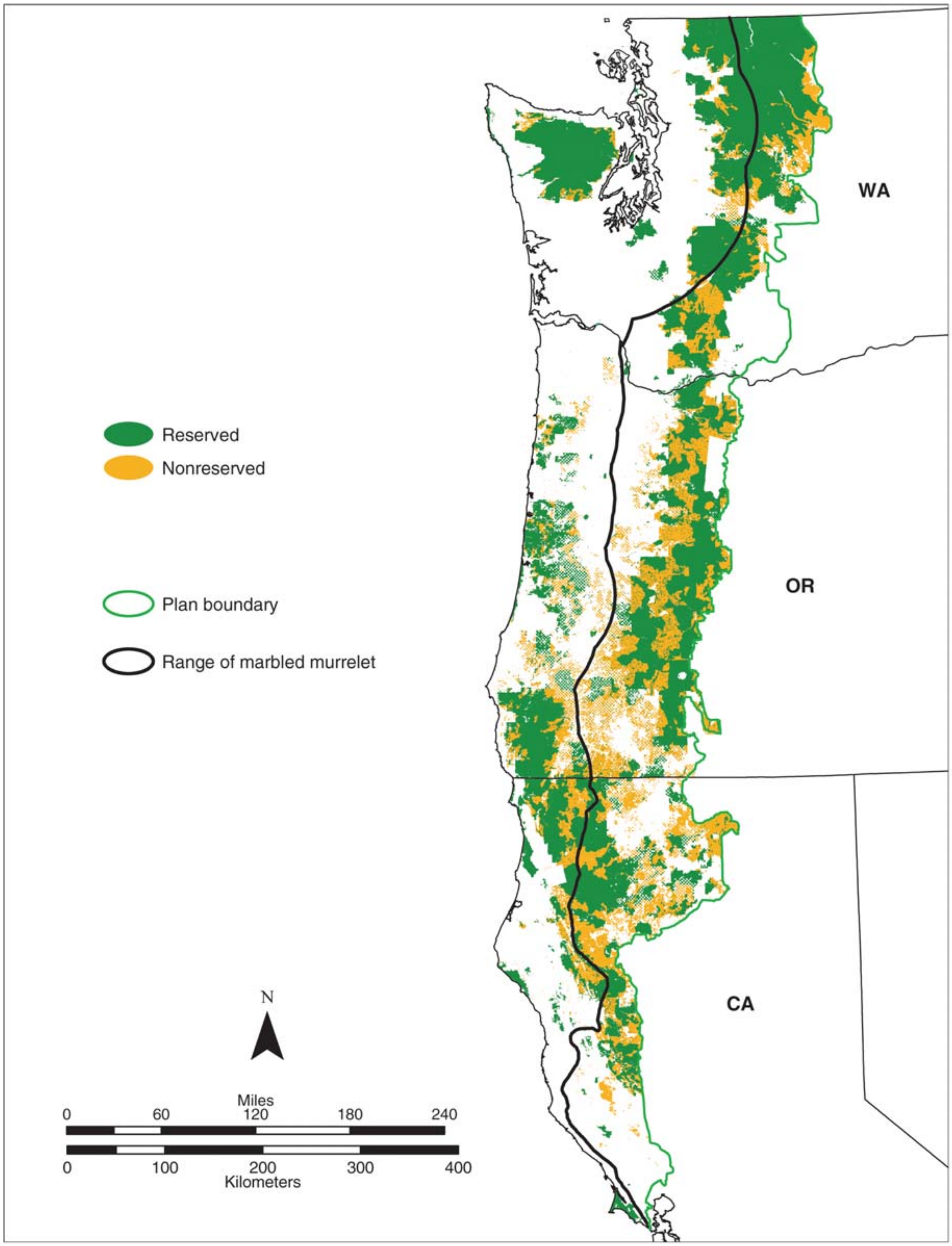

Figure 4-4—Reserved and nonreserved lands in the Northwest Forest Plan area.

Table 4-5—Upper elevation limit by provinces of marbled murrelet nesting behavior detected from 1994 to 2001 occupancy surveys

Province	Marbled murrelet elevation feet limit
Olympic (east side)	4,000
Olympic (west side)	3,500
Washington Western Cascades	3,800
Oregon Coast Range	2,900
Oregon Western Cascades	4,200
Oregon Klamath Mountains	4,200
California Coast Range	2,400
California Klamath Mountains	4,200

Source: Raphael et al., chapter 5 this volume.

To estimate the amount of potential nesting habitat as a function of the odds ratios, we (1) transformed the asymmetrically distributed odds ratios[12] to a symmetrical interval of -1 to 1, with equal odds at zero, by using Yule's Q [odds ratio -1/odds ratio + 1] (Yule and Kendall 1950); (2) sorted the PSUs by their transformed odds ratios into 10 equal classes from -1 to 1 (i.e., >0.8-1, >0.6-0.8, and so on) for a given analysis unit (e.g., by states), and (3) summed the geographic area represented by each PSU in each class. The estimates of the amount of potential nesting habitat are displayed by the Plan, state, and physiographic province, by reserved/nonreserved, and by inland habitat Zones 1 and 2. The units for these predictions, in theory, are the total number of acres of nonoverlapping 150-acre sites predicted as potential nesting habitat; however, for practical purposes we reported the units as acres of potential nesting habitat with transformed odds ratios equal to or higher than the average among occupied sites.

We derived standard errors of potential nesting habitat estimates using bootstrap techniques in Efron and Tibshirani (1993). There are three sources of variability that we could model by using bootstrap techniques:

- The selection of the "best" predictor variables in the logistic regression model.
- The estimation of the coefficients in the logistic regression model given a particular selection of the "best" variables.
- The sampling error associated with the "random" selection of grid inventory sites.

Given that accounting for all three sources of variability through a bootstrap process would be exceedingly time consuming, we performed 1,000 bootstrap runs to account for sources (2) and (3) where we believe that most of the variability lies.

Primary sample units and areas of estimation— The number of PSUs and total area of U.S. Forest Service and BLM land in the Plan area, both inside and outside inland habitat Zones 1 and 2 of the marbled murrelet, are shown in table 4-6a. There are about 9.2 million acres of federal land in Zones 1 and 2, with about two-thirds of that in Zone 1. The number of PSUs and the area surveyed are displayed in tables 4-6b and 4-6c by state, agency, and physiographic province for federal land within the potential range of the marbled murrelet. Among federal lands, the PSUs covered about 7.4 million acres; all were of U.S. Forest Service and BLM land. Small, often isolated areas on Forest Service and BLM lands, such as in the Western Lowlands Province of Washington, and all National Park Service lands were not part of the grid inventory in the potential range of the marbled murrelet, accounting for acre disparities in tables 4-6.

Table 4-7 provides the number of PSUs in this study and their area contribution (sum of PSU area expansion factors) to the total area studied by zone, state, and physiographic province. The total area studied is about 6.7 million acres, based on 2,765 PSUs. This differs slightly from table 4-6b, which shows that about 7.4 million acres were available for study with 2,895 PSUs (totals added between BLM and U.S. Forest Service). Table 4-7 is based on the available PSU habitat data (described below), whereas table 4-6b is based on GIS queries of intersecting

[12] Odds ratios, without transformation, lie on an interval of zero to infinity, where equal odds (value of 1) is highly skewed towards zero.

Table 4-6a—Area and primary sample unit (PSU) totals within the boundary of the Plan

	Area			No. PSU's		
Geographic span	**Nonfederal**	**Federal**	**Total**	**Nonfederal**	**Federal**	**Total**
	Acres			*Number*		
Outside murrelet zones 1 and 2	12,264,063	15,593,512	27,857,576	5,422	0	5,422
Murrelet zone 1	16,226,384	6,221,043	22,447,427	0	2,096	2,096
Murrelet zone 2	3,728,284	3,005,707	6,733,990	0	799	799
Total (Plan)	32,218,731	24,820,262	57,038,992	5,422	2,895	8,317

Table 4-6b—Area and primary sample unit PSU totals for each state, federal agency, and murrelet zone

		Murrelet zone					
State	**Agency**[a]	**1**	**2**	**Total**	**1**	**2**	**Total**
		Acres			*No. of PSUs*		
California	BLM	124,775	22,296	147,071			
	DoD	1,637		1,637			
	FWS	127		127			
	NPS	183,398		183,398			
	USFS	774,876	865,905	1,640,782	127	130	257
	Total	1,084,814	888,201	1,973,016	127	130	257
Oregon	BLM	909,268	378,817	1,288,085	526	207	733
	DoD	727		727			
	FWS	4,354	5,574	9,928			
	NPS	101	430	531			
	USFS	1,563,362	151,058	1,714,420	736	85	821
	Total	2,477,811	535,879	3,013,690	1,262	292	1,554
Washington	DoD	107,407		107,407			
	FWS	4,521		4,521			
	NPS	967,980	384,900	1,352,881			
	USFS	1,578,509	1,196,726	2,775,235	707	377	1,084
	Total	2,658,417	1,581,626	4,240,044	707	377	1,084
Plan area	BLM	1,034,043	401,113	1,435,156	526	207	733
	DoD	109,771		109,771			
	FWS	9,002	5,574	14,576			
	NPS	1,151,479	385,330	1,536,809			
	USFS	3,916,748	2,213,689	6,130,437	1,570	592	2,162
	Total	6,221,043	3,005,707	9,226,750	2,096	799	2,895

[a] BLM = Bureau of Land Management, DoD = Department of Defense, FWS = U.S. Fish and Wildlife Service, NPS = National Park Service, and USFS = U.S. Forest Service.

Table 4-6c—Area and primary sample unit (PSU) totals for each province, federal agency, and murrelet zone

		Murrelet zone					
Province	**Agency**[a]	**1**	**2**	**Total**	**1**	**2**	**Total**
		Acres			*No. of PSUs*		
California Coast	BLM	122,961	8,463	131,424			
	DoD	1,637		1,637			
	FWS	127		127			
	NPS	183,398		183,398			
	USFS	24,233	7,191	31,424	5	1	6
	Total	332,356	15,654	348,010	5	1	6
California Klamath	BLM	1,814	13,833	15,647			
	USFS	750,644	858,714	1,609,358	122	129	251
	Total	752,458	872,547	1,625,005	122	129	251
Oregon Coast	BLM	752,375	37,157	789,532	429	17	446
	DoD	727		727			
	NPS	101		101			
	USFS	625,282		625,282	328		328
	Total	1,378,485	37,157	1,415,642	757	17	774
Oregon Klamath Mountains	BLM	153,142	285,604	438,745	95	154	249
	NPS		430	430			
	USFS	938,080	151,058	1,089,138	408	85	493
	Total	1,091,222	437,091	1,528,313	503	239	742
Oregon Western Cascades	BLM	797	53,981	54,777	1	36	37
	Total	797	53,981	54,777	1	36	37
Oregon Willamette	BLM	2,954	2,076	5,030	1		1
	FWS	4,354	5,574	9,928			
	Total	7,308	7,650	14,958	1		1
Washington Eastern Cascades	NPS		6	6			
	USFS		283,682	283,682		80	80
	Total		283,687	283,687		80	80
Washington Olympic Peninsula	FWS	78		78			
	NPS	898,022		898,022			
	USFS	630,815		630,815	298		298
	Total	1,528,915		1,528,915	298		298
Washington Western Cascades	NPS	68,259	384,895	453,154			
	USFS	947,133	913,044	1,860,178	409	297	706
	Total	1,015,393	1,297,939	2,313,332	409	297	706

Table 4-6c—Area and primary sample unit (PSU) totals for each province, federal agency, and murrelet zone (continued)

		Murrelet zone					
Province	**Agency**[a]	**1**	**2**	**Total**	**1**	**2**	**Total**
		Acres			*No. of PSUs*		
Washington Western Lowlands	DoD	107,407		107,407			
	FWS	4,443		4,443			
	NPS	1,698		1,698			
	USFS	561		561			
	Total	114,109		114,109			
Plan area	BLM	1,034,043	401,113	1,435,156	526	207	733
	DoD	109,771		109,771			
	FWS	9,002	5,574	14,576			
	NPS	1,151,479	385,330	1,536,809			
	USFS	3,916,748	2,213,689	6,130,437	1,570	592	2,162
	Total	6,221,043	3,005,707	9,226,750	2,096	799	2,895

[a] BLM = Bureau of Land Management, DoD = Department of Defense, FWS = U.S. Fish and Wildlife Service, NPS = National Park Service, and USFS = U.S. Forest Service.

Table 4-7—Number of primary sample units (PSUs) studied, and total area, and PSU area mean by zone, state, and physiographic province

State/zone	Physiographic province	PSUs	PSUs sum	Mean	Standard deviation
		Number	*Number*	*Acres*	
Zone 1					
California	Coast	4	27,960	6,990	0
	Klamath	104	655,776	6,306	1,937
	Total California	108	683,736	6,331	1,905
Oregon	Western Cascades	1	1,952	1,952	
	Coast Range	750	1,375,729	1,834	571
	Klamath Mountains	496	1,078,035	2,173	1,166
	Willamette Valley	1	1,939	1,939	
	Total Oregon	1,248	2,457,655	1,969	874
Washington	Olympic Peninsula	290	588,341	2,029	1,132
	Western Cascades	381	819,160	2,150	1,173
	Total Washington	671	1,407,501	2,098	1,156
Total	Zone 1	2,027	4,548,892	2,244	1,431
Zone 2					
California	Coast	1	6,990	6,990	
	Klamath	106	696,603	6,572	1,932
	Total California	107	703,593	6,576	1,924
Oregon	Western Cascades	36	64,571	1,794	392
	Coast Range	17	27,362	1,610	655
	Klamath Mountains	238	429,626	1,805	441
	Total Oregon	291	521,558	1,792	451
Washington	Eastern Cascades	63	153,836	2,442	1,676
	Western Cascades	277	779,639	2,815	1,901
	Total Washington	340	933,474	2,746	1,864
Total	Zone 2	738	2,158,626	2,925	2,160
Zones 1 and 2					
California	Coast	5	34,950	6,990	0
	Klamath	210	1,352,379	6,440	1,934
	Total California	215	1,387,329	6,453	1,913
Oregon	Western Cascades	37	66,523	1,798	387
	Coast Range	767	1,403,091	1,829	574
	Klamath Mountains	734	1,507,660	2,054	1,006
	Willamette Valley	1	1,939	1,939	
	Total Oregon	1,539	2,979,213	1,936	814
Washington	Eastern Cascades	63	153,836	2,442	1,676
	Olympic Peninsula	290	588,341	2,029	1,132
	Western Cascades	658	1,598,799	2,430	1,556
	Total Washington	1,011	2,340,976	2,316	1,465
Total	Zones 1 and 2 total	2,765	6,707,518	2,426	1,684

polygons and all PSUs planned for study. About 5 percent of the PSUs planned for study (about 500,000 acres) had coordinates on federal land but could not be installed because a grid location was inaccessible (e.g., cliff or open water), thus nullifying them for habitat projections. About 250,000 acres (approximately 2.5 percent of the total area under consideration) remains uncharacterized without an explanation. The contribution of a single PSU to federal land area ranges from 371 to 11,567 acres in the potential range of the marbled murrelet; the average is 2,494 acres. Although all provinces in the Plan area in the potential range of the marbled murrelet are displayed, only five provinces had sufficient numbers of PSUs (on U.S. Forest Service and BLM lands) to assess results at this scale, namely the California Klamath; Oregon Coast Range and Klamath; and Washington Olympic Peninsula and Western Cascades provinces (see tables 4-6b and 4-6c).

Results

What Is Marbled Murrelet Nesting Habitat?

Table 4-8 shows the Plan Area and Zone-1-Only models and the combination of habitat variables that best predict occupancy associated with nesting while adjusting for detection rates by state. The top 30 candidate models of all possible subsets of predictor habitat variables are shown in the appendix tables. The Plan Area and Zone-1-Only models had the same set of habitat variables selected as the highest ranked models (lowest AICc value in the appendix tables), although individual estimates of the coefficients differed slightly (table 4-8). Both models indicate that probability of murrelet occupancy is higher at sites that are closer to the sea (SEADIST), are relatively flat (SLOPEM), have less solar radiation or are likely topographically cooler (SRIM), have relatively fewer conifers above pole size (CDEN25; ≥10 in d.b.h.), have relatively more basal area of conifer trees above pole size (BA10; >10 in d.b.h.), and have relatively more basal area of larger diameter trees (BA30Low; >30 in d.b.h.).

The most important predictor variables of marbled murrelet potential nesting habitat relative to the other variables in the model were distance to coastline (SEADIST) and solar radiation index (SRIM) (table 4-9). In the Plan Area model, nearness to coastline (SEADIST) was the most important multivariate predictor of potential nesting habitat, with the next five ranked variables showing much

Table 4-8—Habitat variables, estimated coefficients, and standard errors for the Plan Area and Zone-1-Only models adjusted for detection rates by state

	Plan Area model coefficients (Zones 1 and 2)		Zone-1-Only model coefficients	
Variable[a]	Estimate	Standard error	Estimate	Standard error
Intercept	25.8399	6.5559	27.2262	7.0669
SEADIST	-0.07283	0.01340	-0.05515	0.01552
SLOPEM	-0.1207	0.04071	-0.1068	0.04074
SRIM	-0.00081	0.000222	-0.00087	0.000241
CDEN10	-0.01034	0.003300	0.01048	-0.003301
BA10	0.02145	0.007806	0.01950	0.007505
BA30Low	0.02683	0.01264	0.02063	0.01307
WA detection rate	0.5705	0.02158	0.5705	0.02158
CA detection rate	0.7830	0.02740	0.7820	0.02745
OR detection rate	0.2325	0.02532	0.2324	0.02541

[a] Variable acronyms are defined in table 2.

Table 4-9—Ranking of predictor variables in Plan Area and Zone-1-Only models based on the change in AICc when each variable is removed individually from the top models

	Plan Area model (Zones 1 and 2)		Zone-1-Only model	
Rank	Variable[a]	Change in AICc[b]	Variable	Change in AICc
1	SEADIST	43.4	SRIM	16.3
2	SRIM	14.0	SEADIST	13.4
3	BA10	11.1	CDEN10	11.8
4	CDEN10	9.9	BA10	11.1
5	SLOPEM	7.6	SLOPEM	6.9
6	BA30Low	2.4	BA30Low	1.9

[a] Variable acronyms are defined in table 2.

[b] AICc = Akaike's Information Criterion, a relative goodness-of-fit of statistical models.

lower influence. Solar radiation was the most important multivariate habitat predictor in the Zone-1-Only model, and it also ranked second in the Plan Area Model. In the Zone-1-Only model, the top four to five variables showed similar strength on the habitat predictions, as changes in AICc values (from the model with all of the final variables) were alike when each was removed from the model. The changes in AICc values within models suggested that habitat prediction data from Zone 2 of the Plan Area model had a strong influence, increasing the importance of distance to coastline.

The level of agreement between the actual survey location data (occupied and absent) and the model predictions for these sites ranged from 72 to 83.5 percent (by using probability $\geq$0.5 and <0.5 as the indicator of occupied and absent, respectively) correctly predicted among states and between models (tables 4-10a and 4-10b). The models predicted correctly a higher proportion of matches of occupied and absent in Oregon and lower in California; however, the relative differences were modest at about 7 to 11 percent between models.

What Is the Amount of Potential Nesting Habitat?

Comparing prediction models—

Overall, our models predicted low odds ratios[13] of suitable nesting habitat for marbled murrelets on federal lands (U.S. Forest Service and Oregon BLM) compared to odds ratios on the set of occupied sites (table 4-11). With the Plan Area model, only about 7 percent of the federal lands (about 466,000 acres) had odds ratios equal to or greater than that of occupied sites, with 99.8 percent of predicted acreage occurring in Zone 1. The Zone-1-Only model predicted about 188,000 more acres of habitat with odds ratios equal to or greater than occupied sites in Zone 1, 594,000 acres total, than the Plan Area model predicted for both zones. Most of the predicted habitat acreage occurred in the lowest intervals of odds ratios, -1.0 to -0.8, with about 74 percent (about 4.95 million acres) in the Plan Area model and about 55 percent (about 2.52 million acres) using the Zone-1-Only model (table 4-11).

The relative standard errors of estimates for odds ratios that were equal to or greater than known suitable nesting habitat are shown in table 4-12 for the Plan Area and Zone-1-Only models. In general, the standard errors were high, >45 percent, and for Zone 2 >100 percent.

Our goal was to predict suitable nesting habitat on federal lands by using a single Plan-wide model. The estimates for Zone 2 have much uncertainty, however. Consequently, we restricted the remainder of this paper to predictions by using the Zone-1-Only model.

Zone 1 estimates—

We compared habitat variable means from two groups of grid inventory plots: those with predicted odds ratios equal to or greater than known suitable plots (higher odds ratios) and those with odds ratio less than this (table 4-3; last two columns). Habitat variable means with higher odds ratios were closer to the coast, had lower mean solar radiation index and density of conifers >10 in d.b.h., and higher conifer basal area of trees >10 and >30 in d.b.h.

[13] Hereafter, the term odds ratios refers exclusively to transformed odds ratios.

Table 4-10a—Counts of observed and predicted site status and percentage of matching status for the Plan Area model

State	Observed status	Predicted status Absent	Predicted status Occupied	Matching
				Percent
California	Absent	0	6	72.0
	Occupied	1	18	
Oregon	Absent	35	5	83.5
	Occupied	8	31	
Washington	Absent	27	8	76.9
	Occupied	7	23	
All states	Absent	63	19	79.9
	Occupied	15	72	

Table 4-10b—Counts of observed and predicted site status and percentage of matching status for the Zone-1-Only model

State	Observed status	Predicted status Absent	Predicted status Occupied	Matching
				Percent
California	Absent	0	6	72.0
	Occupied	1	18	
Oregon	Absent	20	7	78.8
	Occupied	7	32	
Washington	Absent	21	7	75.9
	Occupied	7	23	
All states	Absent	41	20	76.5
	Occupied	15	73	

Table 4-10c—Counts of observed and predicted site status and percentage of matching status for a variation of the Zone-1-Only model excluding solar radiation index

State	Observed status	Predicted status Absent	Predicted status Occupied	Matching
				Percent
California	Absent	2	5	80.0
	Occupied	0	18	
Oregon	Absent	26	1	60.6
	Occupied	25	14	
Washington	Absent	28	0	48.3
	Occupied	30	0	
All states	Absent	55	7	59.1
	Occupied	51	36	

Table 4-11—Relative percent of odds ratios and acres of habitat area predicted from grid inventory plots in 10 intervals for U.S. Forest Service and Bureau of Land Management land by using the Plan Area (n = 2,765) and Zone-1-Only (n = 2,027) models

Odds ratio[a]	Plan Area model	Zone 1-Only model	Plan Area model	Zone 1-Only model
	– – – – – Percent– – – – –		*– – – Thousand acres – – –*	
-1.0 to -0.8	73.8	55.4	4,951	2,518
-0.8 to -0.6	8.8	13.9	592	631
-0.6 to -0.4	5.4	7.6	360	347
-0.4 to -0.2	2.8	5.6	191	256
-0.2 to 0.0	2.2	4.5	147	203
0.0 to 0.2	2.2	2.7	146	124
0.2 to 0.4	1.3	3.1	87	141
0.4 to 0.6	1.3	2.4	88	107
0.6 to 0.8	1.2	2.4	81	110
0.8 to 1.0	1.0	2.5	64	112
Total	100	100	6,707	4,549

[a] Odds ratios were transformed by using Yule's Q; a value of zero is equivalent odds to known nesting habitat.

Table 4-12—Estimated acres, bootstrap standard error, and relative standard error of the acres with odds ratios[a] greater than zero based on the inventory grid locations for the Plan Area and Zone-1-Only prediction models of U.S. Forest Service and Bureau of Land Management land

Logistic regression model	Prediction zone	Area: Estimated	Area: Bootstrap standard error	Area: Relative standard error
		------ *Acres* ------		--------- *Percent* ---------
Plan Area	1	451,726	211,819	46.9
	2	14,521	15,481	106.6
	1 and 2	466,247	223,121	47.9
Zone-1-Only	1	593,632	306,236	51.6

[a] Odds ratios are calculated with respect to average habitat conditions of sites occupied by marbled murrelets.

These patterns were similar to our patterns observed for prediction model dependent variables at occupied versus absent sites, except mean solar radiation (table 4-3). The average of the mean solar radiation index of occupied sites (27,014) was close to absent sites (27,108), whereas grid inventory sites with higher odds ratios had substantially lower mean solar radiation index values (23,375) than sites with lower odds ratios (27,077).

The amounts of habitat area by state, province, and reserve status in 10 intervals of odds ratios are shown in table 4-13a and 4-13b and cumulative habitat area in seven intervals from 1.0 to -0.4 in figure 4-5a through 4-5c. Amount of habitat area was low in most of the intervals of odds ratios, except for the two lowest intervals of odds ratios ranging from -1.0 to -0.6 where about 69 percent of the total area occurred (table 4-14a and fig. 4-5d). At the highest odds ratios, ranging from 1.0 to 0.6, Washington had the most habitat area, 7.4 percent (about 104,000 acres) of the federal land within Washington, whereas Oregon had 3.5 percent (about 85,000 acres) and California 4.8 percent (about 33,000 acres) (table 4-13a). In the other intervals, ranging from 0.6 to -1.0, Oregon had the most habitat area (table 4-13a). California had the fewest acres in all intervals except from -0.6 to -0.2 (table 4-13a). By physiographic province, the largest amount of habitat with odds ratios equal to or greater than on occupied sites was in the Oregon Coast Range (about 191,000 acres) and on Olympic Peninsula (about 141,000 acres) (table 4-13a). The Olympic Peninsula had the highest relative proportions, 24.0 percent of the federal land with odds ratios equal to or greater than on occupied sites, and the Oregon Coast Range and California Klamath Mountains, with 13.4 and 13.2 percent, respectively.

About 77 percent of the federal lands in Zone 1 are in a reserved land allocation (table 4-13b). Among the 10 intervals of odds ratios, the proportion of reserved land ranged from 70.6 percent to 91.0 percent (table 4-13b). Although most of the habitat area with higher odds ratios of being suitable was predicted as within reserve land allocation, most of reserved land had low odds of being suitable for nesting (table 4-13b and fig. 4-5c). The highest proportion of federal land in reserves with odds ratios equal to or greater than on occupied sites was in Washington, 16.9 percent; Oregon had 14.2 percent and California 12.7 percent (table 4-13b).

We subjectively partitioned the 10 intervals of odds ratios into four likely habitat suitability classes analogous to Raphael et al. (chapter 5, this volume) (fig. 4-5d), and summed the habitat amounts in each class by state, province, and land allocation (table 4-14). The proportion of federal land in the four classes, unsuitable (odds ratios -1 to -0.8), lower (-0.8 to -0.4), moderate (-0.4 to 0), and higher suitability (0 to 1.0) was 55.4, 21.5, 10.1, and 13.1 percent, respectively, suggesting that most federal lands have low

Table 4-13a—Zone 1 habitat area in 10 transformed odds ratio[a] intervals from the Zone-1-Only model, by state and province for U.S. Forest Service and Bureau of Land Management land

	Transformed odds ratio										
Physiographic province	-1.0 to -0.8	-0.8 to -0.6	-0.6 to -0.4	-0.4 to -0.2	-0.2 to 0	0 to 0.2	0.2 to 0.4	0.4 to 0.6	0.6 to 0.8	0.8 to 1.0	Total
California											
Coast		13,980	6,990	6,990							27,960
Klamath	369,161	74,667	57,865	50,520	15,924	7,776	32,154	14,766	20,358	12,582	655,776
California total	369,161	88,647	64,855	57,511	15,924	7,776	32,154	14,766	20,358	12,582	683,736
Oregon											
Western Cascades	1,952										1,952
Coast Range	686,020	212,455	107,178	83,524	95,996	67,371	42,985	38,719	22,257	19,225	1,375,729
Klamath Mountains	542,152	209,662	110,549	61,484	55,606	19,181	22,041	13,494	16,994	26,872	1,078,035
Willamette Valley	1,939										1,939
Oregon total	1,232,063	422,117	217,727	145,008	151,602	86,552	65,026	52,213	39,251	46,097	2,457,655
Washington											
Olympic Peninsula	283,957	78,686	44,425	23,719	16,459	16,942	27,705	20,330	36,210	39,908	588,341
Western Cascades	633,086	41,362	19,664	30,042	19,246	12,463	15,837	19,716	14,674	13,071	819,160
Washington total	917,043	120,048	64,089	53,760	35,706	29,405	43,543	40,046	50,884	52,978	1,407,501
Plan area total	2,518,267	630,812	346,671	256,279	203,232	123,733	140,723	107,025	110,493	111,657	4,548,892

[a] Odds ratios were transformed by using Yule's Q; a value of zero is equivalent odds to known nesting habitat.

Table 4-13b—Zone 1 habitat area in 10 transformed odds ratio[a] intervals from the Zone-1-Only model, by reserve status and state for U.S. Forest Service and Bureau of Land Management land

	Transformed odds ratio										
State	-1.0 to -0.8	-0.8 to -0.6	-0.6 to -0.4	-0.4 to -0.2	-0.2 to 0	0 to 0.2	0.2 to 0.4	0.4 to 0.6	0.6 to 0.8	0.8 to 1.0	Total
Nonreserve:											
California	122,020	18,266	6,990	35,754	1,944	7,776	5,592	7,776	6,990		213,110
Oregon	404,176	83,649	34,674	28,495	25,195	6,001	9,459	1,880	7,151	1,880	602,560
Washington	154,412	30,072	13,291	11,032	1,882	3,822	3,765		1,882	9,036	229,193
Nonreserve total	680,608	131,987	54,954	75,280	29,022	17,599	18,816	9,656	16,023	10,916	1,044,862
Reserve:											
California	247,141	70,381	57,865	21,756	13,980		26,562	6,990	13,368	12,582	470,626
Oregon	827,887	338,468	183,053	116,513	126,406	80,551	55,567	50,333	32,100	44,217	1,855,095
Washington	762,631	89,976	50,799	42,729	33,823	25,583	39,778	40,046	49,001	43,942	1,178,308
Reserve total	1,837,659	498,825	291,716	180,998	174,209	106,134	121,907	97,369	94,470	100,742	3,504,030
Plan area:											
California	369,161	88,647	64,855	57,511	15,924	7,776	32,154	14,766	20,358	12,582	683,736
Oregon	1,232,063	422,117	217,727	145,008	151,602	86,552	65,026	52,213	39,251	46,097	2,457,655
Washington	917,043	120,048	64,089	53,760	35,706	29,405	43,543	40,046	50,884	52,978	1,407,501
Plan area total	2,518,267	630,812	346,671	256,279	203,232	123,733	140,723	107,025	110,493	111,657	4,548,892

[a] Odds ratios were transformed by using Yule's Q; a value of zero is equivalent odds to known nesting habitat.

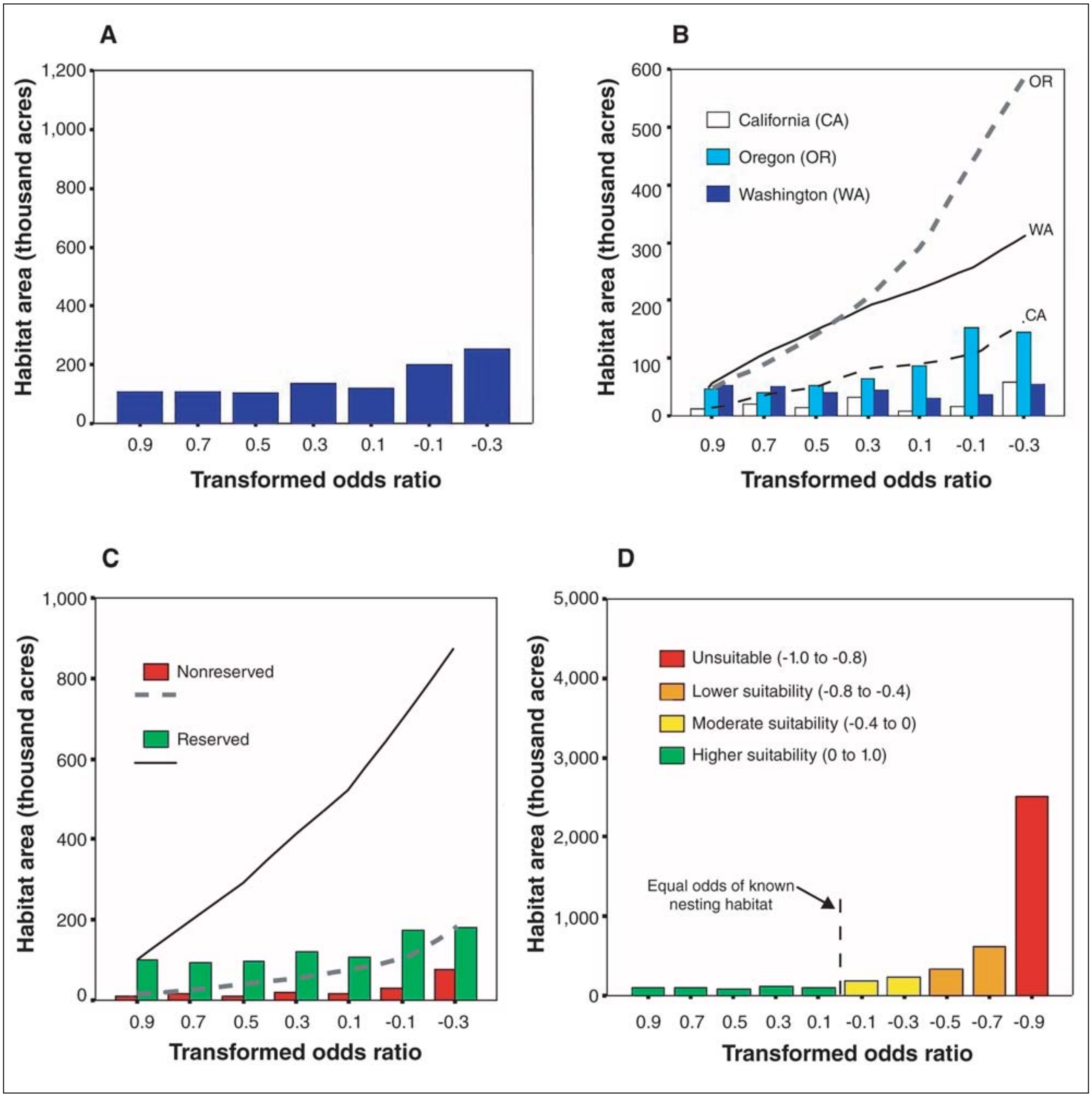

Figure 4-5—Histogram of Zone-1-Only model estimated habitat area in projected odds ratios classes and line graph of cumulative area (A) Zone 1, (B) state, and (C) land allocation. Graph (D) is odds ratios placed into four potential suitability classes. Odds ratios were transformed by using Yule's Q; a value of zero is equal odds of know nesting habitat.

Table 4-14a—Zone 1 habitat area (acres) in four categories by state and province for U.S. Forest Service and Bureau of Land Management land

Physiographic province	Projected suitability: Unsuitable (odds ratios[a] -1.0 to -0.8)	Lower suitability (odds ratios -0.8 to -0.4)	Moderate suitability (odds ratios -0.4 to 0)	Higher suitability (odds ratios 0 to 1.0)	All
California					
Coast		21	7		28
Klamath	369	133	66	88	656
California total	369	154	73	88	684
Oregon					
Western Cascades	2				2
Coast Range	686	320	180	191	1,376
Klamath Mountains	542	320	117	99	1,078
Willamette Valley	2				2
Oregon total	1,232	640	297	289	2,458
Washington					
Olympic Peninsula	284	123	40	141	588
Western Cascades	633	61	49	76	819
Washington total	917	184	89	217	1,408
Plan area total	2,518	977	460	594	4,549

[a] Odds ratios were transformed by using Yule's Q; a value of zero is equivalent odds to known nesting habitat.

Table 4-14b—Zone 1 habitat area (acres) in four categories by reserve status and state for U.S. Forest Service and Bureau of Land Management land

State	Projected suitability: Unsuitable (odds ratios[a] -1.0 to -0.8)	Lower suitability (odds ratios -0.8 to -0.4)	Moderate suitability (odds ratios -0.4 to 0)	Higher suitability (odds ratios 0 to 1.0)	All
Nonreserve:					
California	122	25	38	28	213
Oregon	404	118	54	26	603
Washington	154	43	13	19	229
Nonreserve total	681	187	104	73	1,045
Reserve:					
California	247	128	36	60	471
Oregon	828	522	243	263	1,855
Washington	763	141	77	198	1,178
Reserve total	1,838	791	355	521	3,504
Plan area:					
California	369	154	73	88	684
Oregon	1,232	640	297	289	2,458
Washington	917	184	89	217	1,408
Plan area total	2,518	977	460	594	4,549

[a] Odds ratios were transformed by using Yule's Q; a value of zero is equivalent odds to known nesting habitat.

odds ratios of being suitable for nesting. Oregon had the most land area in all suitability classes, and California the least. In comparing the proportion of area in suitability classes for each state, the highest within-state percentages for the moderate and low suitability classes were in Oregon and the highest for the unsuitable and higher suitability classes were in Washington. The proportions of habitat area in reserves among unsuitable, lower, moderate, and higher suitability classes were 73.0, 80.9, 77.3, and 87.7 percent, respectively (table 4-14b).

Discussion

We present results that predicted the baseline amount of nesting habitat by using data from marbled murrelet location surveys and data from a systematic inventory grid that covers federal land in the Plan area. We consider this modeling approach experimental in our quest to develop new methods to monitor long-term habitat changes that are repeatable, effective, and cost efficient. To develop and assess this new approach, we relied mostly on existing data. We used marbled murrelet survey location data as a basis to develop our habitat model, as did Raphael et al. (chapter 5, this volume); these data inherently have some potential biases that are unquantifiable, which may have influenced our results. We discuss these potential biases below.

We assumed that murrelet identification and observations of "nesting" behavior were correct; however, actual nesting at most sites was never validated. Marbled murrelet location surveys were not conducted according to any planned survey design and were not random with respect to the potential range of potential nesting habitat, both structurally and geographically. Most location surveys were done prior to management activities, usually timber sales, in areas that were identified as probable marbled murrelet nesting habitat. We developed our "training" vegetation data set from plot-level measurements and GIS data taken from the marbled murrelet location survey sites. The plot-level data were gathered from points randomly located at the sites; however, the degree to which these points truly reflect the actual location attributes selected for nesting by murrelets is unknown. In using the survey location data to predict nesting occupancy, we made adjustments to marbled murrelet detection probabilities by modifying standard logistic regression equations for inequitable detection effort, number of detections, and detection scales (table 4-8a). Although there are some potential biases in the survey data, we believe that our estimates are an improvement over the original estimates in the Plan because they (1) are based on actual habitat measurements rather than observations and opinion (in the Plan) and (2) established a consistent baseline of data for the Plan area from which long-term monitoring can be readily replicated.

We used the logistic regression equations based on the marbled murrelet survey location data to predict the odds ratios of inventory grid locations as nesting habitat relative to occupied sites and to estimate the amount of nesting habitat for different geographic areas or allocations. We estimated the variability associated with (1) the logistic regression coefficients and (2) the "random" selection of grid inventory sites, by using a bootstrap process; the variability estimates were high: about 52 percent for Zone 1 and substantially higher for Zone 2 at 107 percent (table 4-12). Some of this variability can be attributed to our sample size. Logistic regression uses maximum likelihood estimation, which requires a large sample to provide reliable estimates. If samples are too small, then high standard errors are likely (Grimm and Yarnold 1995). Our logistic regression prediction model for Zone 1 is based on 149 sites surveyed both for occupancy and habitat predictor variables. Grimm and Yarnold (1995) suggest that at least 50 samples may be needed per predictor variable; we had 8 predictor variables. Another possible cause of the high relative standard errors is that only a relatively small proportion of our predicted area, 13 percent, had odds ratios equal to or exceeding that of known nesting habitat.

Our models correctly predicted occupancy of the actual survey location data (occupied or absent) at about 75 percent (table 4-10b; Zone-1-Only model), a modest improvement over chance alone. Our prediction models, however, were focused on distinguishing habitat differences between occupied and absent sites that probably were more similar than dissimilar. According to protocol (Evans-Mack et al. 2003), only sites potentially suitable for nesting were to be surveyed, thus increasing the likelihood that habitat characteristics overlapped broadly between occupied and absent sites. Whereas, if the occupied and absent survey sites had been selected from a much broader pool of forest conditions, including improbable nesting sites, the level of prediction agreement certainly would have been much higher. Potential false absences in the survey data, that is, an absent site is suitable for nesting but a marbled murrelet is not detected, also may have affected the prediction agreement. An "absent" site may not be occupied for nesting because of factors other than habitat conditions, including limited food resources near nesting habitat.

The most important predictor variables of marbled murrelet potential nesting habitat were distance to coastline and solar radiation index (table 4-8b). In the Plan Area model, nearness to coastline was the "dominant" predictor variable among those selected (table 4-9). Although distance to coast is an important habitat selection variable to murrelets (Meyer and Miller 2002; Meyer et al. 2002; Zharikov et al., 2006; reviewed in Nelson et al., chapter 2, this volume), its relative strength in the Plan Area multivariate equation is questionable because the survey location data from Zone 2, in retrospect, were a set of 20 "absent" sites farther inland than all other sites. Because of the uncertainty, we changed our prediction model to focus on just Zone 1. For now, the availability of just "absence" sites from Zone 2 suggests that this zone is marginal for murrelet nesting, but to what extent is unclear. Surveys have been done nearly exclusively on lands identified for logging that are outside reserved land allocations, leaving large gaps in area surveyed. Thus, additional surveys are needed in Zone 2 that are distributed systematically, target geographic areas that have not been surveyed, and broadly cover the range of potential forest characteristics associated with murrelet nesting habitat.

Compared to the Plan Area model, no single predictor variable dominated the Zone-1-Only model. In this model, four to five habitat variables strongly influenced the multivariate predictions, the most important being decreasing mean solar radiation index and distance to coastline (table 4-9). Because of marbled murrelet's dependence on the marine environment for food and to breed successfully, distance to coastline is likely to be important in most any terrestrial habitat modeling for this species (see Nelson et al., chapter 2, this volume). What distance to coastline provides in murrelet habitat modeling is to delineate and prioritize (e.g., probability) the geographic extent and distance to coast of potential habitat, but it does not provide the site-level characteristics of habitat selection.

The importance of solar radiation (i.e., maximum shortwave radiation given slope, aspect, elevation, solar angle, length of daylight, and shading from nearby landforms) as a predictive habitat variable has not been documented for marbled murrelets, and we are not aware of any other studies that have used it. Unlike the other variables in our prediction equation, the differences between absent and occupied survey sites were not readily apparent for the mean solar radiation variable (table 4-3). When comparing two groups by using logistic regression, such as occupied and absent sites, the data groups of individual predictor variables are not expected to be different in order to make an important contribution to a multivariate prediction equation. However, because this habitat variable has not been used before for this species, further examination of this variable seemed warranted. To do this, we developed an alternative prediction model for Zone 1 without the mean solar radiation variable. Using the same methods as our previous habitat modeling, the top scoring model had three predictor variables: distance to coast (-), density of conifers >10 in d.b.h. (-), and basal area of coniferous trees >10 in d.b.h. (+). With this set of variables our overall prediction capabilities of occupied and absent survey sites in Zone 1 decreased from about 76 percent (including mean solar radiation index) to about 59 percent, affecting Washington the most (tables 4-10b and 4-10c). This implies that the mean solar radiation index is a key part of our prediction model for Zone 1 and that murrelets are more likely to nest in locations with less solar radiation, or probably cooler environments, in combination with the other important predictor variables. Some probable habitat features associated with increasingly cooler environments include increased presence of moss on branches that is used as a nesting substrate, increased complexity of forest structure that could provide increased cover and shade; and increased number of larger trees (e.g., more trees survive wildfire) and large branches for nesting—in addition to potential physiological reasons such as thermoregulation (see chapter 2 for review marbled murrelet habitat relations).

Our baseline estimates indicate that in general the Plan area has low amounts of forest with predicted high odds ratios of providing suitable habitat for marbled murrelet nesting. Although our habitat estimates may be experimental at this stage, the patterns of our estimates (table 4-13) generally follow new mapping estimates for federal land by Raphael et al. (chapter 5, this volume [table 5-9]). Our new approach may be promising as a way to evaluate the long-term effectiveness of the Plan to maintain and recover potentially suitable marbled murrelet nesting habitat, especially at broad scales. This would be accomplished by evaluating the amount and rate of change among intervals of odds ratios over time (e.g., in assigned classes of suitable nesting habitat). And, because these estimations are based on remeasured ground-based plots, we expect them to be more reliable than interpreted satellite imagery for long-term monitoring. Yet, there are distinct limitations of relying solely on systematic, grid-based estimations. Mostly, such estimations have no specific location context and cannot be used for small-scale, individual project planning, whereas a mapping approach can.

To shift this study from largely experimental to broader applications, the highest priority is to reduce estimate standard errors by enhancing the data used to make habitat predictions. Most improvement will come by substantially increasing the number of survey sites (occupied and absent) sampled for habitat predictor variables. With eight predictor variables, and the possible need for about 50 samples per predictor variable (sensu Grimm and Yarnold 1995), several hundred more sites would be needed. Other needs are to (1) widen the scope of predictor variables, focusing especially on different types of habitat structure variables (e.g., trees with large branches) and (2) restrict the modeling to where murrelets are known to nest. For the latter, this means refining the true breeding range of the species, at least on federal land, by delineating geographic areas in Zones 1 and 2 that are both environmentally suitable for nesting and have a reasonable chance of being occupied—thus eliminating the need for dual zones in the Plan. Key to accomplishing this is building a comprehensive murrelet location database from surveys done by various state and federal land management units, which never has been done in a collaborative and centralized manner for the Plan area; map those survey locations; and then carry out additional surveys prioritized systematically to fill gaps in existing information by geographic area and habitat conditions.

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Metric Equivalents

When you know:	Multiply by:	To find:
Inches (in)	2.54	Centimeters
Feet (ft)	.3048	Meters
Acres (ac)	.405	Hectares
Square miles (mi^2)	2.59	Square kilometers
Square feet per acre (ft^2/ac)	.229	Square meters per hectare

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APPENDIX

Table 4-15a—Thirty Plan Area candidate models of all possible sets of predictor habitat variables and Alkaike information criterion (AICc) weights

Variables in model	AICc	AICc weight
SEADIST SLOPEM SRIM CDEN10 BA10 BA30Low	1413.650943	0.078
SEADIST SLOPEM SRIM CDEN10 BA30Low BA30High	1413.806001	.072
SEADIST SLOPEM SRIM CDEN10 BA10 BA30High	1413.839485	.071
SEADIST SLOPEM SRIM BA10 BA30Low BA30High	1414.733963	.045
SEADIST SLOPEM SRIM CANSTR CDEN10 BA10 BA30Low	1415.252901	.035
SEADIST SLOPEM SRIM CANSTR CDEN10 BA10 BA30High	1415.364345	.033
SEADIST SLOPEM SRIM CANSTR CDEN10 BA30Low BA30High	1415.437334	.032
SEADIST SLOPEM SRIM BA30Low BA30High	1415.587220	.029
SEADIST SLOPEM SRIM CDEN10 CDEN30 BA10 BA30Low	1415.627016	.029
SEADIST SLOPEM SRIM CDEN10 CDEN30 BA30Low BA30High	1415.749485	.027
SEADIST ELEVM SLOPEM SRIM CDEN10 BA10 BA30Low	1415.749656	.027
SEADIST ELEVM SLOPEM SRIM CDEN10 BA30Low BA30High	1415.884804	.025
SEADIST SLOPEM SRIM CDEN10 BA10 BA30Low BA30High	1415.947289	.025
SEADIST ELEVM SLOPEM SRIM CDEN10 BA10 BA30High	1415.966749	.024
SEADIST SLOPEM SRIM CDEN10 CDEN30 BA10 BA30High	1416.005389	.024
SEADIST SLOPEM SRIM CANSTR BA10 BA30Low BA30High	1416.407148	.020
SEADIST SLOPEM SRIM CDEN30 BA10 BA30Low BA30High	1416.525880	.018
SEADIST SLOPEM SRIM CDEN10 BA10	1416.526792	.018
SEADIST ELEVM SLOPEM SRIM BA10 BA30Low BA30High	1416.691566	.017
SEADIST SLOPEM SRIM CDEN30 BA30Low BA30High	1416.803229	.016
SEADIST ELEVM SLOPEM SRIM BA30Low BA30High	1417.077923	.014
SEADIST SLOPEM SRIM CANSTR BA30Low BA30High	1417.192961	.013
SEADIST SLOPEM SRIM CANSTR CDEN10 CDEN30 BA10 BA30	1417.211456	.013
SEADIST ELEVM SLOPEM SRIM CANSTR CDEN10 BA10 BA30L	1417.347573	.012
SEADIST SLOPEM SRIM CANSTR CDEN10 CDEN30 BA30Low B	1417.373963	.012
SEADIST ELEVM SLOPEM SRIM CANSTR CDEN10 BA10 BA30H	1417.485318	.011
SEADIST ELEVM SLOPEM SRIM CANSTR CDEN10 BA30Low BA	1417.512220	.011
SEADIST SLOPEM SRIM CANSTR CDEN10 CDEN30 BA10 BA30	1417.516487	.011
SEADIST SLOPEM SRIM CANSTR CDEN10 BA10 BA30Low BA7	1417.568343	.011
SEADIST SLOPEM SRIM CANSTR CDEN10 BA10	1417.738604	.010

Table 4-15b—Thirty Zone-1-Only candidate models of all possible sets of predictor habitat variables and Alkaike information criterion (AICc) weights

Variables in model	AICc	AICc weight
SEADIST SLOPEM SRIM CDEN10 BA10 BA30Low	1449.813219	0.07010
SEADIST SLOPEM SRIM CDEN10 BA10	1450.081325	.06131
SEADIST SLOPEM SRIM CDEN10 BA30 BA30Low	1450.347515	.05367
SEADIST SLOPEM SRIM CDEN10 BA30	1450.516568	.04932
SEADIST SLOPEM SRIM CANSTR CDEN10 BA10	1451.300183	.03333
SEADIST SLOPEM SRIM CDEN10 CDEN30 BA10 BA30Low	1451.375688	.03210
SEADIST SLOPEM SRIM CANSTR CDEN10 BA10 BA30Low	1451.384629	.03195
SEADIST SLOPEM SRIM CANSTR CDEN10 BA30	1451.783856	.02617
SEADIST SLOPEM SRIM CDEN10 BA10 BA30 BA30Low	1451.814898	.02577
SEADIST SLOPEM SRIM CANSTR CDEN10 BA30 BA30Low	1451.947419	.02412
SEADIST SLOPEM SRIM CDEN10 CDEN30 BA30 BA30Low	1452.086641	.02249
SEADIST ELEVM SLOPEM SRIM CDEN10 BA10 BA30Low	1452.145823	.02184
SEADIST SLOPEM SRIM CDEN10 BA10 BA30	1452.240923	.02082
SEADIST ELEVM SLOPEM SRIM CDEN10 BA10	1452.340514	.01981
SEADIST SLOPEM SRIM CDEN10 CDEN30 BA10	1452.379757	.01943
SEADIST SLOPEM SRIM BA10 BA30 BA30Low	1452.591509	.01748
SEADIST ELEVM SLOPEM SRIM CDEN10 BA30 BA30Low	1452.680223	.01672
SEADIST ELEVM SLOPEM SRIM CDEN10 BA30	1452.775385	.01594
SEADIST SLOPEM SRIM CDEN10 CDEN30 BA30	1452.813003	.01564
SEADIST SLOPEM SRIM CANSTR CDEN10 CDEN30 BA10 BA30	1452.904632	.01494
SEADIST SLOPEM SRIM BA10 BA30	1452.960431	.01453
SEADIST SLOPEM SRIM CANSTR CDEN10 BA10 BA30 BA30Low	1453.326967	.01210
SEADIST SLOPEM SRIM CANSTR CDEN10 BA10 BA30	1453.399825	.01167
SEADIST SLOPEM SRIM CDEN10 CDEN30 BA10 BA30 BA30Low	1453.578373	.01067
SEADIST ELEVM SLOPEM SRIM CANSTR CDEN10 BA10	1453.609666	.01050
SEADIST SLOPEM SRIM CANSTR CDEN10 CDEN30 BA10	1453.619217	.01045
SEADIST SLOPEM SRIM CANSTR CDEN10 CDEN30 BA30 BA30Low	1453.673146	.01018
SEADIST ELEVM SLOPEM SRIM CDEN10 CDEN30 BA10 BA30Low	1453.734500	.00987
SEADIST ELEVM SLOPEM SRIM CANSTR CDEN10 BA10 BA30Low	1453.751464	.00978
SEADIST SLOPEM SRIM BA30 BA30Low	1453.910287	.00904

Chapter 5: Spatially Explicit Estimates of Potential Nesting Habitat for the Marbled Murrelet

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Abstract

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The primary objectives of the Effectiveness Monitoring Plan for the marbled murrelet (*Brachyramphus marmoratus*) include mapping baseline nesting habitat (at the start of the Northwest Forest Plan) and estimating changes in that habitat over time. Using vegetation data derived from satellite imagery, we developed two approaches to model habitat suitability. First, we used expert judgment to reclassify 22 previously established late-successional and old-growth forest classes into four classes of murrelet nesting habitat suitability. Second, we used Ecological Niche Factor Analysis to compute habitat suitability scores from vegetation and physiographic attributes based on comparisons of conditions at 111 polygons that were occupied by marbled murrelets and average conditions over the physiographic provinces in which the murrelets occurred. Estimates of amounts of baseline habitat varied with the model used, but all models showed that over 80 percent of baseline habitat on federally administered lands occurred in reserved lands. A substantial amount of baseline habitat occurred on nonfederal lands; amounts of nonfederal habitat differed among provinces. Fire and harvest have led to losses of nesting habitat since the Plan was implemented, with higher rates of loss on nonfederal lands. Ingrowth of large-diameter stands has also occurred, and rates of ingrowth appear to exceed rates of loss of such stands but we are uncertain how much of this ingrowth can be considered nesting habitat. We conclude with comparisons of the efficacies of the different model approaches and discuss implications of our results for future monitoring.

Introduction

The goal of the Effectiveness Monitoring Program for the marbled murrelet (*Brachyramphus marmoratus*) for the Northwest Forest Plan (the Plan) is to evaluate the success of the Plan in maintaining and restoring murrelet populations and nesting habitat throughout the range of the species within the Plan area (Madsen et al. 1999). The first objective of this monitoring program is to estimate a baseline amount and distribution of nesting habitat within the Plan area. The second objective calls for estimating a trend in the amount of habitat as it is lost and gained over time. Through these objectives and the overall strategy for monitoring the Plan (Mulder et al. 1999), which includes developing habitat maps by using vegetation classifications

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derived from satellite images, managers will have information by which to judge the overall success of the Plan in meeting its objectives. Our objective in this chapter is to describe the amount and distribution of potential nesting habitat for the murrelet and changes in its nesting habitat over the first 10 years of the Plan. We use the term "potential" nesting habitat to emphasize the idea that we are describing forest cover that has the attributes of nesting habitat whether or not murrelets are actually using that habitat for nesting. In this analysis, we build on the information gained in chapter 4 (Huff et al., this volume) to build a spatially explicit model that extends to all lands within the range of the murrelet.

Because marbled murrelets depend on marine conditions for foraging and resting, and on forest conditions for nesting, either marine or forest conditions could limit murrelet numbers. Available evidence, reviewed by Ralph et al. (1995), suggests that nesting habitat is more limiting for murrelets. Recent research on the relationships between total numbers of murrelets entering large drainages and amounts of habitat within those drainages has reinforced this notion: there is a strong, positive correlation between murrelet numbers and amount of habitat at the drainage scale (Burger 2001, Raphael et al. 2002). Miller et al. (2002) also found that abundance of murrelets offshore was strongly related to the amount and configuration of adjacent forest habitat with large, old trees. These studies suggest that the amount of nesting habitat is a major driver for murrelet population size. We recognize, however, that marine conditions such as prey abundance, oil spills, gill net fisheries, or sea surface temperature anomalies can exert strong effects that reduce murrelet populations below a carrying capacity set by nesting habitat. The Plan has no control over marine conditions, but managers under the Plan do influence amount and quality of nesting habitat. Therefore, in this chapter we focus on the characteristics of forest conditions related to nesting habitat of murrelets.

The cryptic location of marbled murrelet nests and their secretive behavior during the nesting season continue to challenge our acquisition of knowledge about this species. Because marbled murrelet nests are difficult to locate, sample sizes for nests are small. Therefore, in this study we have used a sample of locations where murrelet behavior suggests nesting and coupled those locations with large-scale satellite imagery to determine the amount of potential murrelet nesting habitat across the Plan area. Nelson et al. (chapter 2, this volume) reviewed the literature and have provided the necessary background information to understand the attributes of forest cover that define potential suitable nesting habitat.

Effectiveness Monitoring Questions

The primary goal of the Effectiveness Monitoring Plan is to evaluate the success of the Plan in maintaining and restoring marbled murrelet nesting habitat and populations on federal lands throughout the Plan area (Madsen et al. 1999). In this chapter, we focus on habitat. Our primary monitoring questions were:

1. What was the baseline amount of nesting habitat in the Plan area?
2. How has the predicted amount of nesting habitat changed within and outside reserves since the Plan was implemented?

The spatial habitat monitoring was also expected to answer additional questions (other than amount) that came from the record of decision and standards and guides that followed the final supplemental environmental impact statement (FSEIS) (USDA and USDI 1994a, 1994b) including:

1. What is the spatial distribution of nesting habitat in the Plan area?
2. How has the distribution of nesting habitat changed within and among reserves and across federal land?
3. How has the fragmentation of nesting habitat changed within and outside reserves?
4. How has the patch size of nesting habitat, including the amount of interior nesting habitat, changed within and outside reserves?

Data Sources

Most of the base data used for the marbled murrelet habitat monitoring were also used for the evaluation of the northern spotted owl (*Strix occidentalis caurina*) habitat (Davis and Lint 2005). Some of our data source descriptions are quoted from that report.

Vegetation Map Data

We used two sources of vegetation information: (1) the Interagency Vegetation Mapping Project (IVMP) in Oregon and Washington (http://www.or.blm.gov/gis/projects/ivmp.asp); and (2) the Classification and Assessment with Landsat of Visible Ecological Groupings (CALVEG, USDA Forest Service 1981) in California (http://www.fs.fed.us/r5/rsl/projects/mapping/). Data from both sources were circa 1994 to 1996, which coincided with the implementation of the Plan.

The IVMP used Landsat scenes from 1992 through 1996 to map vegetation conditions in Oregon and Washington. A regression modeling approach was used to predict vegetation characteristics, including vegetation cover, conifer cover, broadleaf cover, and tree size (Cohen et al. 2001; Fassnacht et al., n.d.). Forest canopy structure was modeled separately by using different methods (Ducey and Moeur 2003[3]). The resulting raster-based maps are 25-m (82-ft) resolution, 0.15 acre per pixel, and are available with either continuous or grouped values.

The CALVEG map products, California's statewide mapping classification system for existing vegetation, are a consistent set of stand-based polygon data layers systematically derived from satellite imagery and geographic information system (GIS) modeling techniques (Schwind et al. 1999). Baseline Landsat thematic mapper (TM) scenes, all from 1994, along with a variety of other existing ancillary data, were used to create the final layers. Vegetation polygons based on life form were systematically derived from the images. Thematic attributes including vegetation type, percentage of tree cover, and tree size and structure were then assigned to the polygons. The thematic attributes generally are class values rather than continuous values. For the area included in our analysis, the average polygon size was about 11 acres with some polygons on forested lands up to 1,600 acres.

Moeur et al. (2005) reported on the accuracy assessments for the IVMP and CALVEG classifications. Quantitative accuracy assessments were performed for every IVMP attribute. Both nonfuzzy (right/wrong) and fuzzy ratings were reported for CALVEG attributes (http://www.fs.fed.us/r5/rsl/projects/mapping/accuracy.shtml). In general, accuracy increased as classes were grouped. Moeur et al. (2005) reported an overall accuracy of 72.8 percent in classifying older forest stands.

National Land Cover Data

The 1992 National Land Cover Data (NLCD) is a consistent, landcover data layer developed by the U.S. Geological Survey (USGS) and the U.S. Environmental Protection Agency (U.S. EPA) for the conterminous United States based on 30-m (98-ft) Landsat TM data (http://eros.usgs.gov/products/landcover/nlcd.html#description Vogelmann et al. 2001). We used the North California 1992 (with 2000 to 2004 updates) data to mask out non-forest-capable pixels from the CALVEG polygon data. Of the 21 land cover types identified in NLCD, we masked out all except deciduous forest, evergreen forest, mixed forest, and transitional (areas of sparse vegetative cover that are dynamically changing from one land cover to another, such as clearcuts, temporary clearings owing to natural causes [fire, flood, etc.], and transition clearings due to changing land use). We did not use NLCD in Washington or Oregon because the IVMP coverages in those states already contained finer resolution information.

Land Use Allocation Data

The Plan land use allocation (LUA) map, with seven management classes, was originally created in 1993 at a coarse scale for regional planning. There have been numerous refinements since that time, including the splitting and addition of classes. In 2002 the Regional Interagency

[3] Unpublished manuscript. On file at: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, P.O. Box 3623, Portland, OR 97208.

Executive Committee requested that these refinements be reviewed and compiled to create a new version of the LUA map. An update process description and digital copy of the LUA data are available at http://www.reo.gov/gis/data/gisdata/index.htm. We used the official 2002 revised LUA data in our analysis. Although improvements were made in the overall accuracy of LUA mapping, including representation of LUAs at a finer resolution, the map product still has limitations. Riparian reserves and matrix allocations are combined, making neither individually identifiable. The variation in size and classification criteria for administratively withdrawn (AW) areas resulted in inconsistent mapping of these areas across the range of the murrelet. Small slivers between adjacent administrative units resulting from inconsistent administrative boundary lines generally disappeared when we converted the polygons to a raster format. Additional discrepancies, such as misidentification of state lands within the Redwood National Park of California, were discovered as we conducted this analysis and will be corrected during the next round of monitoring and planning. In the case of state lands in Redwood National Park, these lands will be managed as reserves with no planned timber harvest, so including them in federal reserves is not misleading.

The allocation classes for federal lands in the LUA map were as follows:

Reserved lands—

- CR – congressionally reserved
- LSR – late-successional reserves
- AMR – adaptive management areas in reserves (AMA acres in the LSR)
- MLSA – managed late-successional areas
- AW – administratively withdrawn
- LSR 3 – marbled murrelet reserved areas
- LSR 4 – spotted owl core areas

Nonreserved lands—

- AMA – adaptive management areas
- MATRIX/RR – Matrix (which contains riparian reserves that were not mapped). Matrix lands outside of riparian reserves are available for logging; restricted logging can also occur within riparian reserves if compatible with aquatic objectives.
- ND – not designated; land that has no Plan land allocation designation.

All the LUAs listed above were used for our marbled murrelet habitat monitoring analysis.

Disturbance Data

Over the first 10 years since the Plan was implemented, habitat has been lost owing to fire and harvest. Based on comparisons of baseline satellite imagery with more recent imagery, Moeur et al. (2005) conducted a change analysis and mapped forest disturbances caused by crown-replacing fire and harvest. Their analysis covered the years from 1996 to 2002 in Washington, 1995 to 2002 in Oregon, and 1994 to 2003 in California.

Other Ancillary Data Sources

We used 1999 USGS National Elevation Data 30-m (98-ft) digital elevation model (DEM) data for elevation and slope (http://gisdata.usgs.gov/NED/).

We used the 1993 version of the terrestrial ecosystem physiographic province boundary coverage (which also defines the Plan area) and the 2004 revised marbled murrelet range coverage to define the extent of our analysis and report outcomes based on these areas. Revisions to the murrelet range were minor and were confined to adjustments to match the range to higher resolution coastlines. As shown in figure 5-1, the marbled murrelet range, consisting of murrelet Zones 1 and 2, covers only a portion of the Plan area. Our analysis covers only lands within the marbled

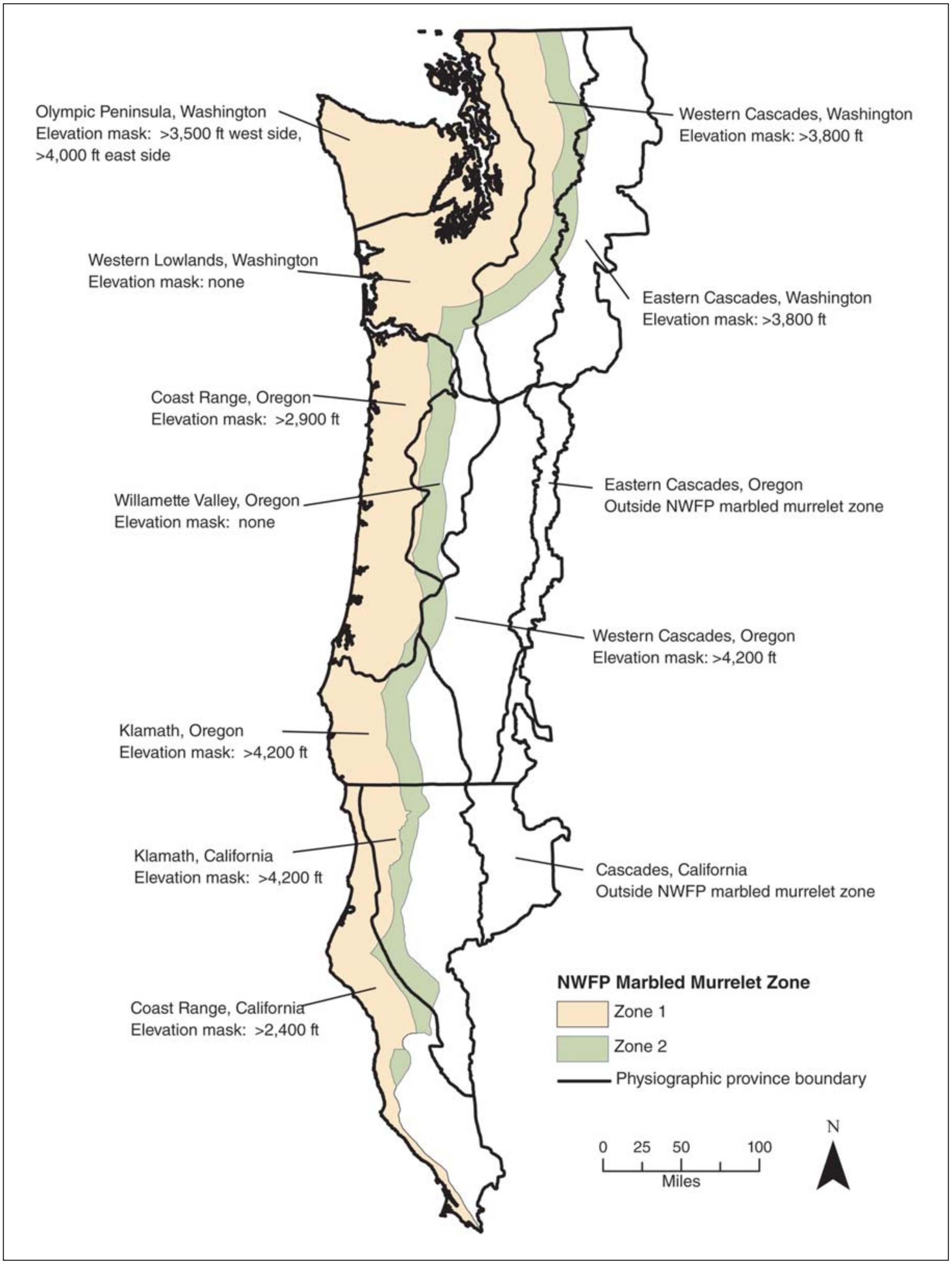


Figure 5-1—Northwest Forest Plan (NWFP) boundary, Zones 1 and 2 of the marbled murrelet range, and physiographic provinces. Elevation masks refer to upper elevation limits of observed nesting by marbled murrelets in each province.

murrelet range. We modified the marbled murrelet conservation zone coverage (USFWS 1997), extending the zone and stratum breaks inland, primarily by following watershed lines, so we could look at relationships between nesting habitat and at-sea murrelet populations. We used the coastline from the physiographic province boundary coverage to estimate distance to coastline (described below). These coverages are available at http://www.reo.gov/gis/data/gisdata/.

Murrelet Locations

Occupied Stands

We used agency records and digital aerial photographs to delineate polygons representing forest stands (areas of relatively homogeneous cover type) in which marbled murrelet occupying behavior was observed during 1994 through 2001. Occupying behaviors included murrelets circling at or below the forest canopy, i.e., including circling above the canopy by no more than 1.0 canopy height; flying through in a straight flight path below the forest canopy; landing in, perching, or departing from a tree; or birds emitting ≥3 calls from a fixed point in a tree within 100 m (328 ft) of an observer (Evans Mack et al. 2003).

Methods used to delineate polygon boundaries are described in Huff et al. (chapter 4, this volume). The marbled murrelet monitoring team randomly selected a subset of these polygons; this sample was the same as the "occupied" polygons analyzed by Huff et al. Because ground-based vegetation data were not available for the Washington Western Lowlands province, Huff et al. did not include this province in their analyses; however, we did include it by randomly selecting a set of murrelet locations for that area that represented both state and private ownerships.

We assumed that occupied polygons represented the breadth of possible marbled murrelet nesting habitat (see McShane et al. 2004; Nelson et al., chapter 2, this volume, for recent reviews). However, the sites originally surveyed by the agencies were not selected randomly. Many of these sites were surveyed prior to timber harvest and so site selection in those cases was guided by timber considerations. The 111 occupied sites we used are distributed among 6 physiographic provinces (fig. 5-2): Olympic Peninsula, Washington (n = 20); Western Lowlands, Washington (n = 20); Western Cascades, Washington (n = 14); Coast Range, Oregon (n = 20); Klamath, Oregon (n = 19); and Coast Range, California (n = 18).

Note that none of these occupied polygons occurred in marbled murrelet Zone 2 (the zone farthest inland from the coastline). We are aware of some records of nest sites or occupied locations inside marbled murrelet Zone 2, but all of these records were outside the period covered by our analysis. Early records were not used because we could not be certain habitat conditions at those sites at the time of the observation could be adequately inferred from baseline conditions (1994 through 1996).

Nests

Marbled murrelet nests have proven difficult to locate, but researchers and managers have found a limited sample in the Plan area. Because there is uncertainty in how occupied locations relate to actual nest sites, we gathered known nest locations to help validate our model results. These locations were obtained from agency records in Washington (n = 33), Oregon (n = 41), and California (n = 8). We compared mean habitat attributes at these nest locations to mean attributes of occupied polygons and the entire area modeled for each state.

Estimating Federal Land Acres

The analysis of marbled murrelet habitat focused primarily on federally administered lands in each physiographic province. To understand the federal contribution to murrelet habitat conservation, we also summarized the amount of habitat on nonfederal lands. For our analysis of federal lands, we included Fish and Wildlife Service (FWS) national wildlife refuges and Department of Defense (DOD) military reservations. An analysis of the percentage of area occupied by older forests on FWS and DOD lands was completed by Moeur et al. (2005).

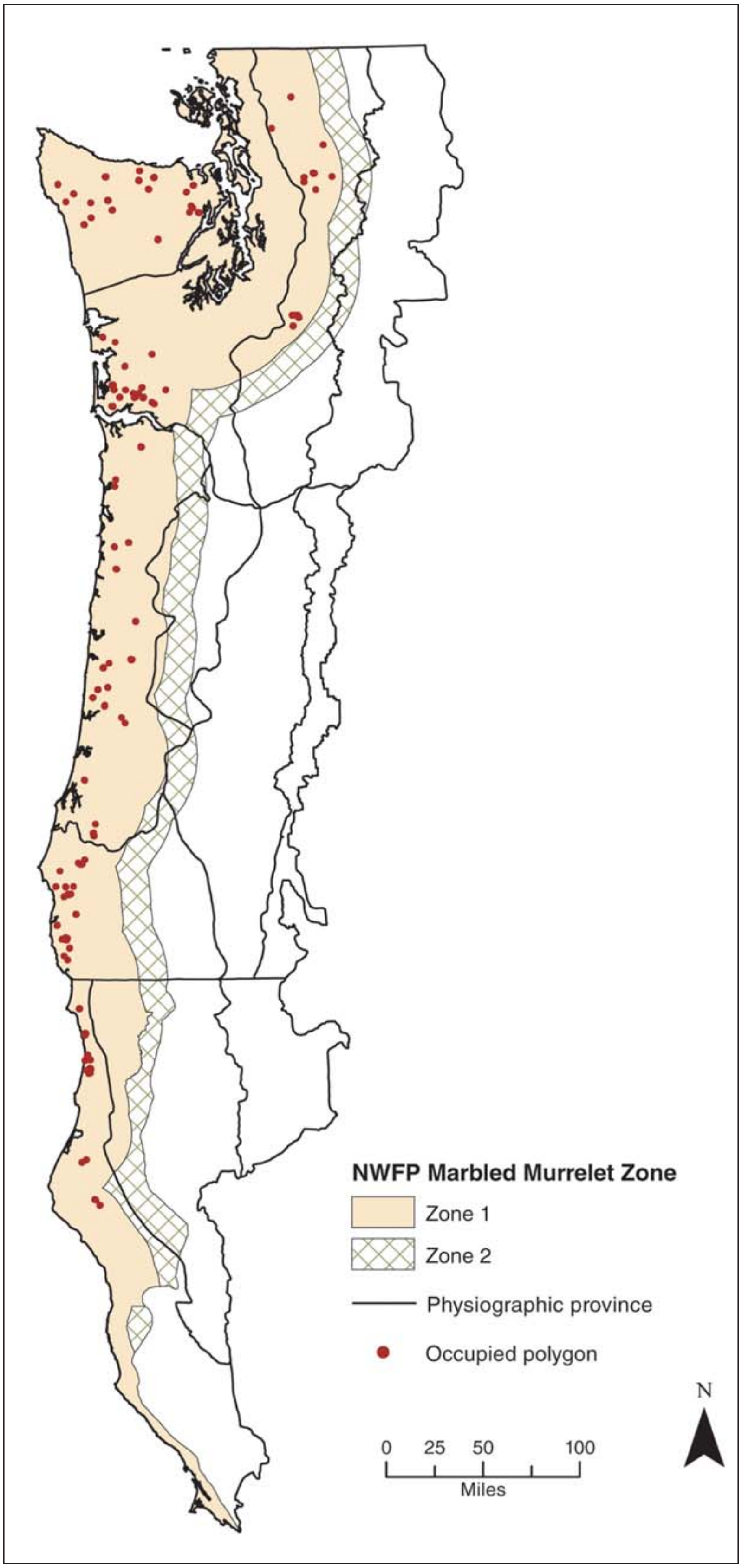


Figure 5-2—Distribution of the 111 polygons in which occupied detections (behaviors thought to be associated with nesting [Evans Mack et al. 2003]) of marbled murrelets have been observed over the years of this analysis (1994 through 2001) in the Northwest Forest Plan (NWFP) area.

Most of the federal land in our analysis is land administered by the USDA Forest Service (FS), USDI Bureau of Land Management (BLM) and the USDI National Park Service (NPS). In the analysis, the combined lands for all three agencies plus the small amount of DOD and FWS are referred to as "federal land" unless otherwise specified.

An ownership grid was derived from the LUA coverage (figs. 5-3a through 5-3c). This GIS-based grid, in combination with the physiographic province grid, was queried to produce estimates of federal land area within each province. Province estimates were summed to obtain state and rangewide estimates.

Estimating Forest-Capable Acres

Not all land in the range of the murrelet is capable of growing forests. Areas that will not develop into forest include rocky lands, barren lands, alpine meadows, snow-covered mountain peaks, and urban developments. Mask grids from IVMP, CALVEG, and NLCD were used to remove non-forest-capable areas from all data used for modeling habitat. Forest-capable land was estimated for each physiographic province and summed to obtain estimates for each state and the range of the murrelet for both federal and nonfederal lands.

Estimating Habitat-Capable Acres (HCA)

Not all of the forest-capable acres are capable of developing marbled murrelet nesting habitat. Examples are forested lands that exceed elevations where murrelets are known to nest. The forest land capable of producing murrelet nesting habitat was estimated by using province-specific upper elevation limits in addition to the forest-capable screen previously described.

The upper elevation limits were identified from our database of occupied murrelet sites. For the Olympic Peninsula, we divided the province into eastern and western subzones and set upper limits for each subzone (following Holthausen et al. 1995). Our upper elevation limits are illustrated in figure 5-1 and vary from no limit in the Washington Western Lowlands and Oregon Willamette Valley provinces (because there were no lands with elevations that exceeded the upper limits for nesting in those provinces) to 4,200 ft in both the Klamath and Western Cascades provinces of Oregon and Klamath province of California.

Modeling Methods

We developed two approaches for the identification of potential murrelet nesting habitat. One was a rule-based or expert judgment definition, and one was a quantitative model.

Because both the spatial resolution (0.15-acre pixels versus much larger polygons of varying size) and attribute resolution (continuous versus predefined classes) varied between the two primary vegetation data sets (IVMP and CALVEG), we initially explored the potential effects of these differences on our models. Our rule-based model used class variables, and both data sets were available as rasters in the classed format required for this model (Moeur et al. 2005), although they differed slightly in spatial resolution (0.15-acre pixels for Washington and Oregon and 0.22-acre pixels for California). Therefore, we focused primarily on performance of the quantitative model to evaluate attribute resolution differences. We classified IVMP continuous data to match CALVEG classes and ran the model for a Washington and Oregon province by using both the continuous and class data at a 0.15-acre pixel resolution. Model output was very similar, with only a slight increase in one of the per-formance indicators (Spearman rank) when using the continuous data. To achieve more consistent results across the murrelet range, we used the class attributes in our models in all provinces. To address the spatial resolution issue we ran the quantitative model for California with CALVEG data only and then with CALVEG data after applying a non-forest-capable filter (from the NLCD, as previously described). Although this did not bring the CALVEG and IVMP data sets to the same attribute resolution, it did provide a means to identify small, non-forest-capable areas within the larger CALVEG polygons. To the extent possible, vegetation map attributes for modeling were made as consistent as possible between the two data sources.

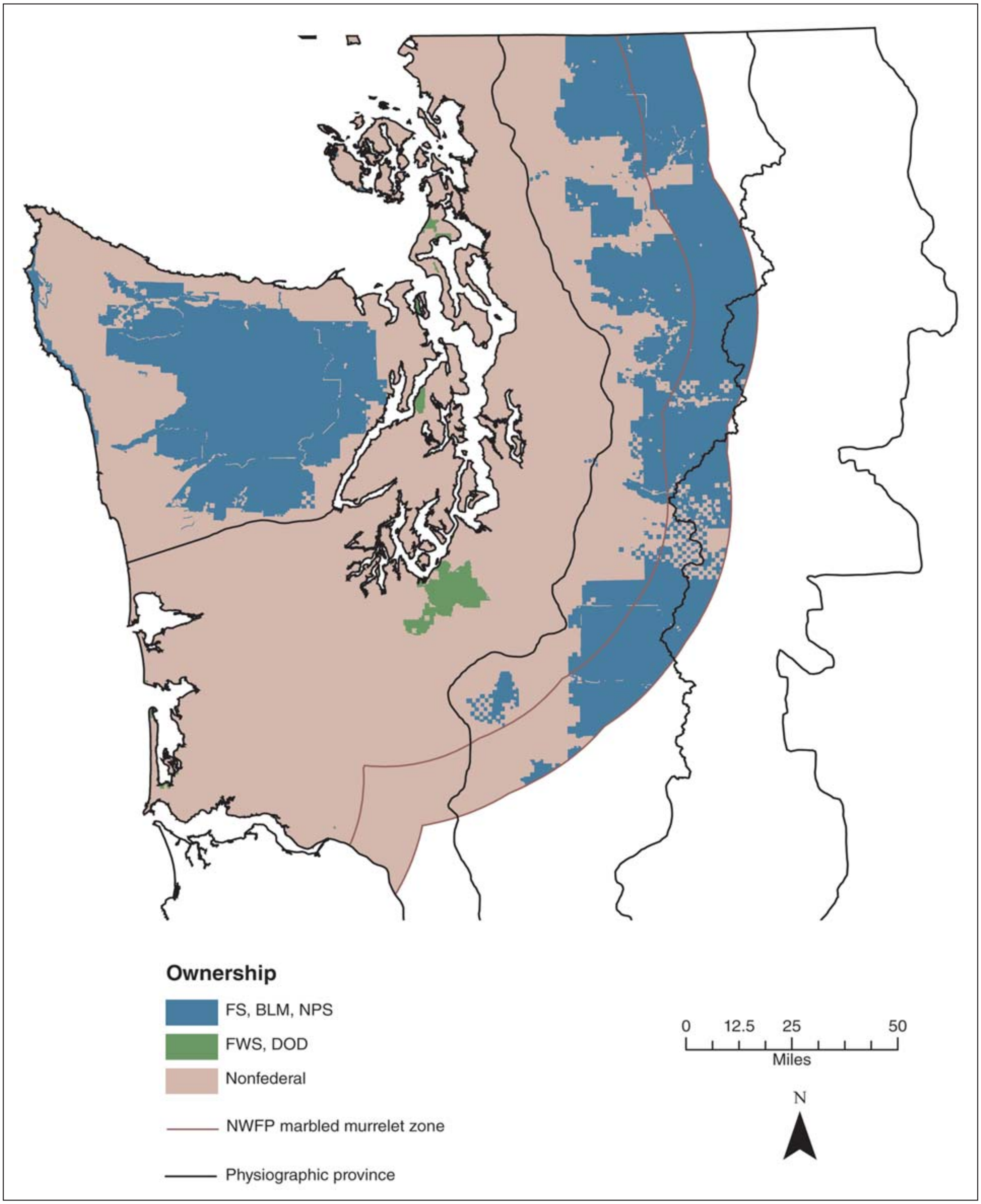


Figure 5-3a—Distribution of federally administered lands in Washington. FS = Forest Service, BLM = Bureau of Land Management, NPS = National Park Service, FWS = Fish and Wildlife Service, DOD = Department of Defense, and NWFP = Northwest Forest Plan.

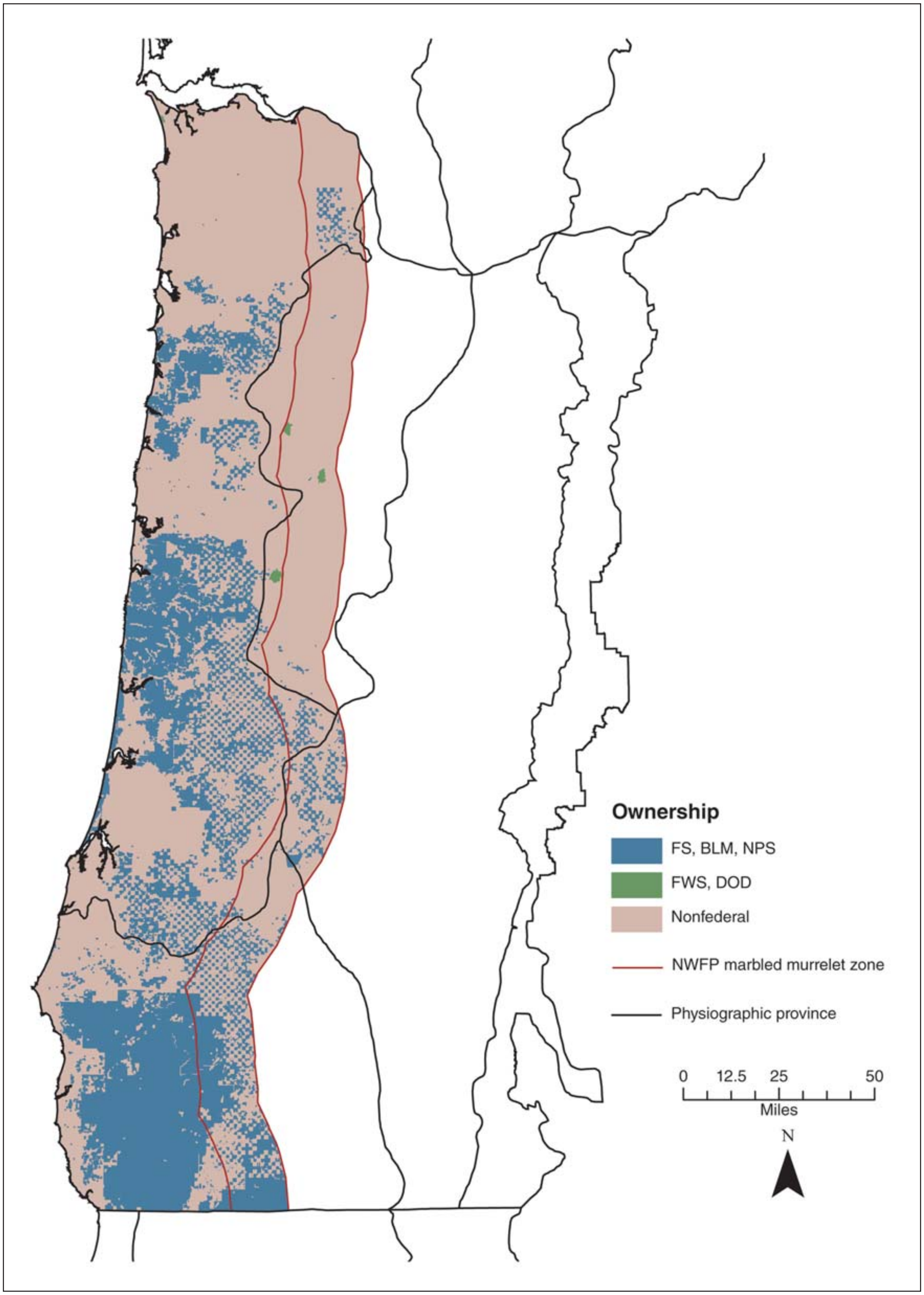


Figure 5-3b—Distribution of federally administered lands in Oregon. FS = Forest Service, BLM = Bureau of Land Management, NPS = National Park Service, FWS = Fish and Wildlife Service, DOD = Department of Defense, and NWFP = Northwest Forest Plan.

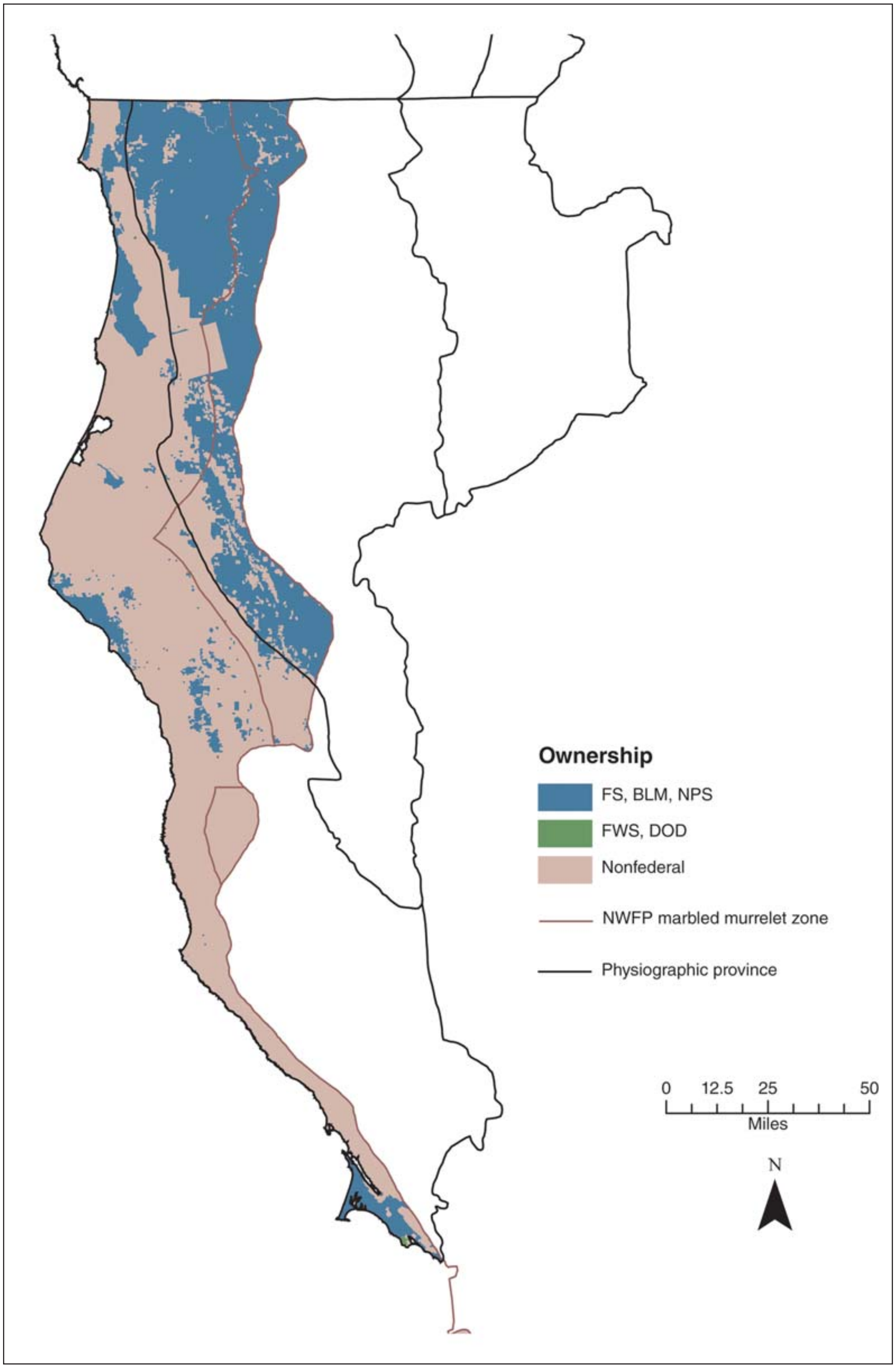


Figure 5-3c—Distribution of federally administered lands in California. See text for additional information on discrepancies in ownership displayed for Redwood National Park. FS = Forest Service, BLM = Bureau of Land Management, NPS = National Park Service, FWS = Fish and Wildlife Service, DOD = Department of Defense, and NWFP = Northwest Forest Plan.

Expert Judgment Model

For this model, we translated the classes of late-successional and old-growth forest (older forest) developed by the older forest monitoring group (Moeur et al. 2005) into levels of suitability as nesting habitat for the murrelet. The older forest classes were defined from four IVMP vegetation attributes (percentage conifer cover, percentage broadleaf cover, quadratic mean diameter [QMD], and percentage of vegetation cover) and one derived attribute (canopy structure, coded as simple or complex). Quadratic mean diameter was estimated based on dominant and co-dominant trees (Moeur et al. 2005). The authors of this chapter evaluated the likelihood that each combination of these attributes might provide conditions suitable to support successful nesting. We assigned to each older forest class a suitability rank in four levels with class 1 indicating the least suitable habitat and class 4 indicating the most highly suitable habitat (table 5-1). We based these assignments on our knowledge of the attributes of preferred nesting habitat (see Nelson et al., chapter 2, this volume). Two additional classes, non-habitat-capable (as described above) and unknown (where we lacked sufficient data to identify a habitat type, but did know it was habitat capable) were also mapped and included in the model.

We then obtained GIS-based grids of the older forest classes for each physiographic province in Washington and Oregon (Moeur et al. 2005) and applied our classification to these 25-m (82-ft) grids to calculate and display the extent of habitat in each of the four suitability classes. We were unable to obtain structure information for the Washington Western Lowlands and Oregon Willamette Valley provinces (IVMP did not produce this attribute because so little federal land occurs in these provinces). In those provinces, we assumed simple structure based on advice from the IVMP group.[4] Although the method was not identical to that of IVMP, the necessary information was extracted from the CALVEG data to derive similar older forest grids at 30 m (98 ft) resolution for the Coast Range and Klamath provinces in California (Moeur et al. 2005).

Patch Area

As noted above, there is evidence that murrelets are more likely to nest in larger patches of contiguous habitat. We defined patches by using spatial software applied to an aggregated or "smoothed" version of our pixel-based map of forest attributes. The "smoothed" maps were generated in a two-step process that changed the spatial resolution of the 25-m (82-ft), 0.15-acre, Expert Judgment classified GIS-based grids for Washington and Oregon into 100-m (328 ft), 2.5-acre grids and 30 m (98 ft), 0.22-acre grids for California into 90-m (295-ft), 2.0-acre grids. The first step, based on a majority rule (the class that appears most often) looked at a 4 by 4 (for 25 m to 100 m) or 3 by 3 (for 30 m to 90 m) nonoverlapping, adjacent block of cells and reassigned the value of all cells in the block to the majority value. We adopted a conservative approach for resolving cases where the 100-m or 90-m block of cells did not have a single majority (two or more classes within a block are tied with having the most number of cells). In those blocks without a single majority on the first pass, the entire highest class habitat (class 4) was temporarily reassigned to the next lowest class (class 3) and the aggregate function rerun. This process was repeated, temporarily reassigning habitat to successively lower classes, until a single majority was achieved in all blocks. The second step converted these grids, now containing blocks of cells with the same values, into grids that match the block size (2.5 acres for Washington and Oregon, and 2.0 acres for California), creating "smoothed," larger resolution rasters suitable for patch analysis. Finally, we used APACK[5] v 2.23 (http://landscape.forest.wisc.edu/projects/apack/), a program to

[4] Moeur, M. 2005. Personal communication. Vegetation monitoring leader, U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, P.O. Box 3623, Portland, OR 97208.

[5] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table 5-1—Reclassification of forest vegetation structure and composition classes used for older forest status and trends analysis (Moeur et al. 2005) into levels of suitability as potential marbled murrelet nesting habitat

Vegetation class[a]	Conifer canopy cover	Quadratic mean diameter	Canopy structure	Species mix	Nesting habitat suitability[b]
	Percent	*Inches*			
1 PF	<10	NA	NA	NA	1
2 SS-D	≥10	<10	Any	≥80% deciduous	1
3 SS-M	≥10	<10	Any	≥20% to <80% either	1
4 SS-C	≥10	<10	Any	≥80% conifer	1
5 SSS-D	≥10	≥10 to <20	Simple	≥80% deciduous	2
6 SSS-M	≥10	≥10 to <20	Simple	≥20% to <80% either	2
7 SSS-C	≥10	≥10 to <20	Simple	≥80% conifer	2
8 SMS-D	≥10	≥10 to <20	Complex	≥80% deciduous	2
9 SMS-M	≥10	≥10 to <20	Complex	≥20% to <80% either	2
10 SMS-C	≥10	≥10 to <20	Complex	≥80% conifer	2
11 MSS-D	≥10	≥20 to <30	Simple	≥80% deciduous	2
12 MSS-M	≥10	≥20 to <30	Simple	≥20% to <80% either	3
13 MSS-C	≥10	≥20 to <30	Simple	≥80% conifer	3
14 MMS-D	≥10	≥20 to <30	Complex	≥80% deciduous	3
15 MMS-M	≥10	≥20 to <30	Complex	≥20% to <80% either	4
16 MMS-C	≥10	≥20 to <30	Complex	≥80% conifer	4
17 LSS-D	≥10	≥30	Simple	≥80% deciduous	3
18 LSS-M	≥10	≥30	Simple	≥20% to <80% either	4
19 LSS-C	>10	≥30	Simple	≥80% conifer	4
20 LMS-D	≥10	≥30	Complex	≥80% deciduous	4
21 LMS-M	≥10	≥30	Complex	≥20% to <80% either	4
22 LMS-C	≥10	≥30	Complex	≥80% conifer	4

[a] Vegetation class names: PF = potentially forested; SS = seedling and sapling; SSS = small single storied; SMS = small multistoried; MSS = medium and large single storied; MMS = medium and large multistoried; LSS = large single storied; LMS = large multistoried. D = deciduous; M = mixed; C = conifer.

[b] Nesting habitat-suitability classes: 1 = unsuitable; 2 = lower suitability; 3 = moderate suitability; 4 = higher suitability

calculate landscape metrics for large-scale data sets, to define patches based on a neighborhood of eight adjacent cells. This approach allows pixels that meet on diagonal corners to merge into a combined patch. We then calculated mean patch size for all patches in each landscape of interest (e.g., province or state).

Ecological Niche Factor Analysis Model

The advantage of the Expert Judgment model is that it can be easily applied to existing data for both the IVMP and CALVEG efforts. It does not rely on the database of murrelet observations, which may be subject to various sampling biases and which has uneven coverage across the set of physiographic provinces, with some provinces having no observations at all. The disadvantage is that it relies on our expert judgment and that judgment may be flawed. Furthermore, it is based solely on five biotic attributes and does not take into account abiotic factors such as slope, aspect, and distance from coastline that are also known to influence habitat suitability (see Nelson et al., chapter 2 and

Huff et al., chapter 4, this volume). For these reasons, we also undertook a quantitative modeling approach where these abiotic characteristics of sites occupied by murrelets could be used to refine our assessment of habitat suitability. We chose Ecological Niche Factor Analysis (ENFA) as a quantitative tool to more objectively model murrelet nesting habitat (Hirzel et al. 2002). One of the main reasons for choosing this model was that it operates on species-presence data (rather than presence-absence), which was the most reliable type of murrelet location data available. We do have a database of unoccupied locations, but these data are problematic. Absence data are often difficult to obtain and frequently not reliable, especially for hard-to-detect species like the murrelet. A given site may be classified as "absent" because (1) the species could not be detected even though it was present (Evans Mack et al. 2003), (2) the species is absent even though the habitat is suitable (such as cases where murrelets are limited by at-sea mortality or foraging habitat), or (3) the habitat is truly unsuitable for the species. Only the last cause is relevant for predictions; false absences arising from the first two situations may considerably bias analyses.

The use of ENFA overcomes the problem of false absences by using only presence data. Our objective was to produce a map that displayed forest meeting the characteristics of murrelet habitat, not to predict the likelihood of occupancy of forest stands on the landscape. That prediction is part of chapter 4 in this volume (Huff et al.). We used the software program BioMapper, version 3.1.2.235, (http://www2.unil.ch/biomapper/, Hirzel et al. 2004) for all ENFA modeling. BioMapper is a package of GIS and statistical tools designed to build habitat suitability models and maps by using ecogeographical variables (environmental, topographical, and anthropic parameters) and species presence data, based on the concept of the ecological niche (Hutchinson 1957). Model inputs are GIS-based grids or rasters.

As noted by Davis and Lint (2005), all habitat suitability models attempt to predict species occurrence based on ecological parameters (Hirzel and Arlettaz 2003, Guisan and Zimmermann 2000). Whether based on expert opinion (deductive models) or based on species location data (inductive models), habitat models attempt to quantitatively describe the environmental space for the ecological conditions where a species occurs. This multidimensional space contains all possible combinations of environmental variables used in the model that occur within the habitat of the species. The ENFA helps to avoid human biases that often occur in deductive modeling and allows the species presence data to "describe" the niche. By comparing the ecological conditions of known presence locations across the landscape to that of the entire area (in our case, the Plan marbled murrelet Zone 1), ENFA summarizes habitat information into a few uncorrelated and standardized ecological factors (fig. 5-4).

These ecological factors contain information about environmental variables that best define the species' niche. The first factor is called the "marginality factor" (μ_G - μ_S in fig. 5-4), which measures the difference between means of pixels among the species polygons and the means among all pixels in the broader global or analysis area. Marginality is calculated as the linear combination of the environmental variables where the average species' environmental values differ most from the average values of the universe of conditions (at the level of the analysis area). A low absolute value (close to 0) indicates that the species tends to live in average conditions throughout the analysis area. A high absolute value (close to 1 or larger) indicates a tendency to occur in extreme habitats. The sign of marginality is relevant: a positive value indicates the species' mean is greater than the mean for the analysis area and a negative value is the converse. The remaining factors are called "specialization factors" (derived from σ_G and •σ_S in fig. 5-4). These factors are also linear combinations of the environmental variables where the distribution of the species presence conditions shows the lowest variance relative to variance of the global conditions (analysis area). Specialization factors help explain how selective the species is in comparison to the available environmental conditions in the analysis area (Hirzel et al. 2002). Specialization varies from 1 to infinity; values closer to 1 indicate the species occurs in a range of conditions similar to the analysis area

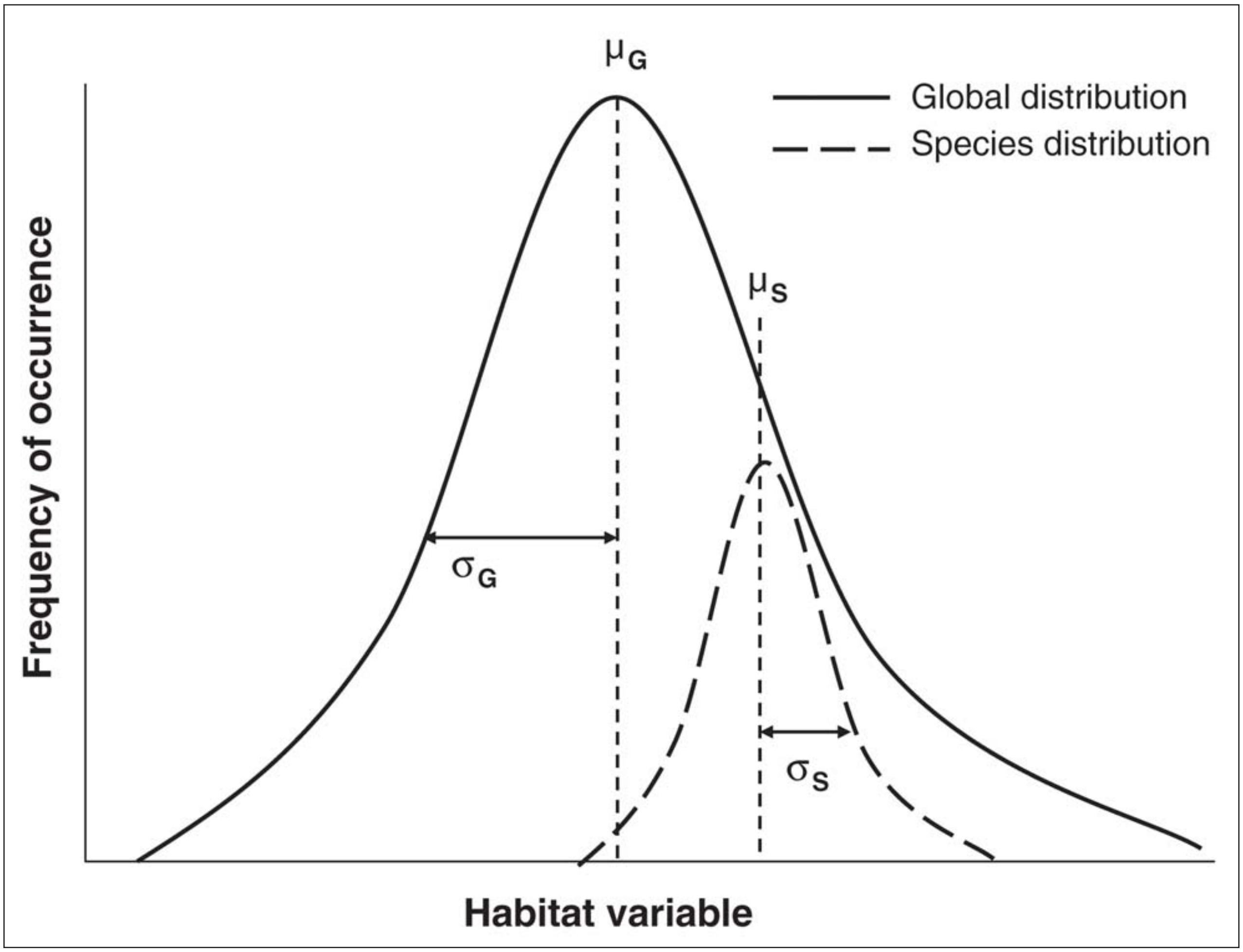


Figure 5-4—This conceptual diagram illustrates features of the Ecological Niche Factor Analysis. The model is based on distributions of a habitat variable for both the global area (the analysis area) and for the area within the analysis area where murrelet presence (i.e., occupied polygons) is known (species distribution). The difference between the global and species means (μ) and standard deviations (σ) defines the marginality and specialization factors, respectively. Figure modified from Hirzel et al. 2002.

as a whole. Tolerance is the inverse of specialization and, because it varies from 0 to 1, is easier to interpret. A low value (close to 0) indicates a relative specialist species that tends to occur in a narrow range of conditions compared to the analysis area; a high value (close to 1) indicates a species that occurs in conditions whose distributions are similar to the analysis area. Most of the relevant ecological information is normally accounted for by the first few factors (marginality factor, plus the first few specialization factors). The signs of specialization and tolerance factors are not meaningful. Together, the marginality and specialization factors define the multidimensional space corresponding to the ecological niche of the species. For a more detailed description of ENFA and the mathematical methods used in the BioMapper software, see Hirzel et al. (2002).

We used two methods to validate the ENFA results. First, we used a *k*-fold cross validation technique (Boyce et al. 2002). For this method, the sample of pixels within occupied polygons is randomly partitioned into a selected number of subsets (we chose five). For each subset, the model is computed based on all but the selected sample and then applied to the selected (or withheld) sample. The habitat suitability scores are grouped into an arbitrary number of bins (we used 10 bins) and we then computed the ratio of the percentage of total pixels within the occupied polygons that occur within the bin to the percentage of total global or analysis area pixels that occur in that same bin. This technique is automated in BioMapper, except that we used a separate spreadsheet to tabulate the results and compute a corrected area-weighted mean Spearman correlation across partitions. We also used the spreadsheet to compute a mean coefficient of variation among partitions to assess variation across partitions.

Our second method of model validation was based on an independent sample of known murrelet nest locations. We overlaid the habitat suitability map with locations of known murrelet nests and computed mean suitability scores for all nests and compared these means with the means from the occupied polygons and with the overall mean for each state. These data allow an independent evaluation of suitability, and help link results describing scores from the set of occupied sites to scores at a set of actual nests.

Murrelet locations—
The ENFA requires a set of murrelet locations. As previously described, we selected 111 occupied polygons (stands) as training sites for this analysis. Because birds may have been detected anywhere within the stand polygon, there is some uncertainty in the habitat at the bird's location. To allow for this discrepancy we chose to define all pixels within each polygon rather than restricting the analysis to a single pixel at each location. All non-habitat-capable pixels within the polygons were masked out prior to ENFA. The remaining set of pixels defined the set of occupied or "species" pixels. Each pixel in this set was then independently assigned values for each environmental variable at that location.

Environmental variables—
We selected 10 variables (table 5-2) to characterize marbled murrelet nesting habitat. Our selection was driven in part by results of the nonspatial modeling work that is also part of the murrelet habitat monitoring effort (Huff et al., chapter 4, this volume) and by the attributes available in the IVMP and CALVEG data.

Murrelets nest preferentially in larger, more contiguous patches of habitat (Meyer 1999; Nelson et al., chapter 2, this volume; Raphael et al. 1995), so we defined two variables that helped assess patch area and contiguity. PATCH8 is a measure of patch area. For this variable, we used the results of the Expert Judgment model and mapped all patches of class 4 (higher suitability) habitat. Patches were defined as described above. We then calculated the area of each class 4 patch and created a new grid with each pixel assigned the value of the area of the class 4 patch that it belonged to. All pixels not in class 4 patches received a value of 0. PCTHIKB is a measure of patch contiguity. For this variable, we used the same map of class 4 habitat, but in this case, we assigned each pixel a value representing the percentage of a 122-acre circular area surrounding that pixel that was class 4 habitat.

We selected a variable representing canopy cover of coniferous trees as an index of density of conifers, reflecting murrelet selection of conifers as nest sites. We selected broadleaf cover to better distinguish sites that might have high QMD but few conifers; sites with high broadleaf cover are unlikely to be used for nesting (Hamer and Nelson 1995, Nelson 1997).

The QMD variable provides an index to tree size; larger trees, especially those greater than 35 in diameter at breast height (d.b.h.), are more likely to support suitable nesting platforms (Hamer 1995; Huff et al., chapter 4, this volume; Nelson et al. 2003; Raphael 2004). We computed the interaction of QMD and conifer cover to better identify those sites with a high density of large-diameter trees. The QMD can be the same in a stand with one large tree as in a stand with 20 large trees, so computing the product of percentage of cover and QMD yields a fuller range of values to describe potential nesting habitat.

Canopy structure was a derived variable computed from an index of canopy complexity (see Moeur et al. 2005, for details) and was coded as 0 for simple and 1 for complex

Table 5-2—Quantitative environmental variables used as input to BioMapper to perform an Ecological Niche Factor Analysis

Abbreviation	Description	Unit
PATCH8	Mean size of patch of class 4 habitat from Expert Judgment model	Continuous variable, in acres; 0 to 217,961
PCTHIKB	Percentage of 122-acre circular area classified as class 4 habitat from Expert Judgment model	Approximately 2-percent increments from 0 to 100
BDLF10	Canopy cover of broadleaved species	10-percent increments from 0 to 100; coded as 0 to 9
CONIF10	Canopy cover of coniferous species	10-percent increments from 0 to 100; coded as 0 to 9
QMD	Quadratic mean diameter	Inches; classes 0-0.9, 1-4.9, 5-11.9, 12-19.9, 20-29.9, 30-39.9, 40-49.9, 50+ Coded by using class midpoints (55 for highest class)
CONIF10*QMD	Interaction of conifer cover and QMD	Product of CONIF10 and QMD
STRUCTURE	Sum of structure values (0 if simple or 1 if complex) across a 49-pixel circular neighborhood around each pixel	Integer from 0 to 49
SLOPE	Slope	Percent; integer from 0 to 87
SOLAR	Index of solar radiation	Index ranges from 0 to 29,618 units
TOSEA	Distance to coastline	Meters; integer from 0 to 76,786

(multilayered) structure. Because BioMapper does not accept Boolean data, we used a neighborhood function to generate a quantitative grid to represent structure. We defined our neighborhood as a four-pixel-radius circle. Each pixel in the new, output grid was assigned the value of the sum of the structure codes in its four-pixel-radius neighborhood, a value from 0 to 49.

Huff et al. (chapter 4) performed a logistic regression based on a sample of occupied and unoccupied murrelet polygons. The top performing model included basal area of trees greater than 30 in d.b.h., basal area of trees greater than 10 in d.b.h., density of trees greater than 10 in d.b.h., solar radiation index, slope, and distance to coastline. We believe our canopy cover and QMD variables and their interaction probably include much of the information in the forest cover variables Huff et al. examined. To reflect the remaining variables, we also included solar radiation, slope, and distance to coastline in our ENFA.

Solar radiation was used as a proxy for aspect and, to a lesser degree, elevation. The solar radiation index grids, one for western Washington, one for western Oregon and one for northwestern California, were created by using a routine written by Lalit Kumar of the University of New England, Australia, and Niklaus Zimmermann of the Swiss Federal Research Institute WSL (shortwave.aml, http://www.wsl.ch/staff/niklaus.zimmermann/progs.html, http://www.ecoman.une.edu.au/staff/lkumar/Posters/Kumar-Solar%20radiation%20modelling.pdf) and a procedure developed by (see footnote 7 in chatper 4) of the U.S. Forest Service, Mount Baker-Snoqualmie National Forest. The program calculates the maximum amount of shortwave radiation received at the surface of the earth for a given period. It takes into account a number of variables including slope, aspect, elevation, solar angle, length of daylight and shading from nearby landforms. The input grids used were 30-m (98-ft) DEMs from the National Elevation Dataset. A specific date was selected to represent the median date of murrelet nest incubation for each state. The dates used are as follows: Washington–19 June; Oregon–26 June; and California–9 June (Hamer and Nelson 1995).

Slope was calculated from 30-m (98-ft) National Elevation Dataset DEMs by using the ArcGIS Spatial Analyst extension (ESRI 1999-2002). Distance to coastline (or marine waters) was calculated from the coastline coverages by using the ArcGIS Spatial Analyst extension (ESRI 1999-2002) straight line distance function.

The model was run separately for each of three broad analysis areas in marbled murrelet Zone 1: Washington (Olympic Peninsula, Western Lowlands, and Western Cascades), Northern Oregon (Coast Range, Willamette Valley, and Western Cascades), and Southern Oregon and California combined (Oregon Klamath, California Coast Range, and California Klamath). We chose three areas as a compromise because BioMapper software could not (computer memory limitations) run a single model covering the entire murrelet range. Single-province models run the risk of excessive sample variation owing to small sample sizes of occupied locations within each province. We chose to combine provinces to overcome both of these limitations and merged the Oregon Klamath with provinces in California because of the similarity of forest cover among these provinces.

An Arc/Info (ESRI 1982-2002) grid was created for each environmental variable for each area modeled. All areas that were not habitat capable, as previously described, were masked out and not modeled. Because all environmental variable maps for a single analysis area had to be consistent (the same cells identified as background or nonbackground), only cells with valid data for all variables could be modeled. The grids were converted to IDRISI format (a geographic analysis and image processing software from Clark Labs, Worcester, MA) for input into BioMapper by using an ArcView 3.3 extension, Av2Idrisi (Holger Schaüble, http://www.terracs.de/ArcView_3_x/Av2Idrisi/av2idrisi.html). The output was disaggregated into provinces and regrouped by states to facilitate comparison between the ENFA and Expert Judgment models. Species (murrelet) and global (regrouped by state) means, standard deviations, and ranges for each of the environmental variables are summarized by province in table 5-3.

Because ENFA requires normally distributed data, all variables were normalized in the BioMapper program by using a Box-Cox transformation (Sokal and Rohlf 1981). Although some variables were not successfully normalized after transformation, ENFA is robust against nonnormal data (Hirzel et al. 2002).

We used the median algorithm to compute habitat suitability (HS) maps. This method, described by Hirzel et al. (2002) gives good results in most situations. It assumes that the best habitat is at the median of the species distribution on each factor and that these distributions are symmetric. Because of the large size of our data sets we were unable to compute HS maps by using the other algorithms available in BioMapper. All 10 factors were retained to build the HS models, and a linear transformation was used to rescale the "raw" HS values to values between 0 and 100 for easier interpretation.

Model applicability—

As shown in figure 5-2, our database includes no occupied murrelet polygons in Zone 2 of the murrelet range. In addition, there were several physiographic provinces for which there were few or no murrelet observations:

- Eastern Cascades, Washington (no observations, province does not extend into marbled murrelet Zone 1)
- Willamette Valley, Oregon (no observations)
- Western Cascades, Oregon (no observations, province has very small overlap with marbled murrelet Zone 1)

Table 5-3—Summary statistics for environmental variables used in Ecological Niche Factor Analysis for polygons occupied by murrelets (species) and analysis area (global)

		Species				Global			
State	Variable[a]	Mean	SD[b]	Min	Max	Mean	SD	Min	Max
Washington			n = 4,380 acres				n = 8,266,660 acres		
	PATCH 8	18,417	54,886	0	217,961	6,340	34,726	0	217,961
	PCTHIKB	42.2	34.3	0	100	10.5	22.6	0	100
	BDLF10	0.7	1.6	0	9	2.4	2.7	0	9
	CONIF10	8.0	1.9	0	9	5.5	3.4	0	9
	QMD	24.8	14.0	0	55	10.8	11.1	0	55
	CONIF10*QMD	207.7	125.1	0	495	76.6	98.8	0	495
	STRUCTURE	27.5	21.6	0	49	9.0	17.1	0	49
	SLOPE	13.8	10.9	0	53	13.1	11.5	0	87
	SOLAR	27,081	2,118	14,193	29,578	27,596	2,215	1,427	29,583
	TOSEA	30,017	17,287	3,477	59,203	26,981	18,671	0	76,786
Northern			n = 1,570 acres				n = 4,883,190 acres		
Oregon	PATCH 8	976	1,794	0	6,081	602	2,807	0	28,017
	PCTHIKB	39.0	19.3	0	91	18.1	22.5	0	100
	BDLF10	1.8	2.0	0	9	2.1	2.0	0	9
	CONIF10	6.8	2.5	0	9	5.3	3.2	0	9
	QMD	26.6	17.2	0	55	13.4	14.6	0	55
	CONIF10*QMD	196.2	146.0	0	495	90.1	118.4	0	495
	STRUCTURE	29.5	18.2	0	49	13.1	18.4	0	49
	SLOPE	20.0	8.9	0	51	17.3	10.2	0	72
	SOLAR	27,166	2,024	14,770	29,588	27,427	2,082	3,880	29,604
	TOSEA	21,747	10,660	7,050	37,585	31,701	18,011	0	76,543
Southern			n = 3,600 acres				n = 4,269,340 acres		
Oregon/	PATCH 8	13,951	20,521	0	54,993	2,302	8,237	0	54,993
California	PCTHIKB	63.8	32.1	0	100	25.8	25.6	0	100
	BDLF10	1.0	1.7	0	9	2.2	2.5	0	9
	CONIF10	7.3	2.0	0	9	5.0	3.2	0	9
	QMD	37.9	19.7	0	55	17.4	12.7	0	55
	CONIF10*QMD	296.9	173.7	0	495	106.0	113.6	0	495
	STRUCTURE	43.0	12.6	0	49	22.5	20.2	0	49
	SLOPE	17.9	8.1	0	56	20.3	9.6	0	67
	SOLAR	27,682	1,589	16,059	29,603	27,098	2,036	7,370	29,618
	TOSEA	12,515	9,656	256	32,211	22,711	15,091	0	65,890

[a] See table 5-2 for variable descriptions.
[b] Standard deviation.

- Klamath, California (only five observations; sample too small for valid independent analysis)

Because of the uneven distribution of observations across provinces, we pooled data among provinces within each of three broad analysis areas as previously described: Washington, Northern Oregon, and Southern Oregon and California. We then ran the BioMapper models for each area. We did not extend our model beyond marbled murrelet Zone 1, and thus excluded the Eastern Cascades of Washington from analysis. Model results apply only to marbled murrelet Zone 1.

Patch area—

We estimated numbers and sizes of patches of habitat (as defined by HS thresholds) by using the same techniques as described previously under the Expert Judgment model. The ENFA modeling used 25-m (82-ft) grids for all three regions, and all were aggregated or "smoothed" to 100-m (328-ft), 2.5-acre, grids for the patch analysis.

Expert Judgment Model Results

Baseline Habitat

Our translation of older forest classes to murrelet nesting HS classes resulted in the classification of about 2.4 million acres of higher suitability habitat (class 4 from table 5-1) on federal lands in marbled murrelet Zones 1 and 2 combined across all provinces (table 5-4, figs. 5-5a through 5-5c) at the time of Plan implementation (we call this "baseline habitat"). This estimate of baseline habitat is slightly lower than the total of 2.6 million acres estimated in the FSEIS (USDA and USDI 1994a: 222) and greater than the estimate of 2.2 million acres of suitable habitat on federal lands reported by McShane et al. (2004) in their recent marbled murrelet status review. The aggregated numbers are surprisingly close, considering we are basing our estimate on completely new vegetation classifications and we imposed elevation limits to nesting habitat that were not considered in the FSEIS. Differences between our estimates and those from the FSEIS vary by province (fig. 5-6); of those provinces with the largest amounts of habitat reported in the FSEIS, our current estimate is lower on the Olympic Peninsula, Oregon Klamath and California Klamath provinces, and greater on the Washington Western Cascades, Oregon Coast Range, and California Coast Range provinces.

In half of the provinces (Olympic Peninsula, Western and Eastern Cascades of Washington, and Oregon and California Klamath) most of the higher suitability (class 4) habitat was on federal land (fig. 5-7). These provinces account for 76 percent of all class 4 habitat on federal land. Across all provinces, we estimate that 41 percent of class 4 nesting habitat occurred on nonfederal lands (table 5-5). The Willamette and Western Lowlands had the highest percentage of nonfederal class 4 habitat, but their combined contribution to total class 4 habitat across the murrelet range was about 2 percent. In the Oregon Coast Range, 54 percent of class 4 potential nesting habitat occurred on nonfederal lands and in the California Coast Range, 84 percent was nonfederal.

On federal lands, most baseline habitat was found within reserves. Over all federal lands, 81 percent of class 4 habitat was found within reserved land use allocations. The proportions of federal habitat in reserves varied among provinces (fig. 5-7). The Western Lowlands had the highest proportion, nearly 100 percent, but this accounted for less than 1 percent of the total federal class 4 habitat. The Olympic Peninsula province, which accounted for 19 percent of the total federal class 4 habitat, had over 97 percent of its habitat in reserves. The Western Cascades of Oregon had the lowest proportion in reserves, 29 percent, but the small portion of this province within the range of the murrelet is mainly in Zone 2 and accounted for less than 1 percent of the total federal higher suitability habitat. Statewide, Washington had the highest percentage of reserved class 4 habitat (93 percent) and accounted for 44 percent of the total reserved class 4 federal habitat. Oregon had 76 percent in reserves and accounted for 36 percent of the total, and California had 71 percent in reserves and accounted for the remaining 20 percent of the total.

Patch Area

Results described above represent total amounts of potential habitat regardless of the size of patches in which that habitat occurs. Table 5-6 and figure 5-8 show that a substantial amount of class 4 habitat occurred in patches >500 or >1,000 acres in most provinces. There were no patches >500 acres of class 4 habitat in the Western Lowlands, Eastern Washington Cascades, Willamette Valley, and Western Cascades of Oregon. The highest percentages of habitat occurring in patches >500 acres or >1,000 acres were on the Olympic Peninsula, reflecting the extensive area of national park and wilderness in that province.

Table 5-4—Summary of estimated area of potential marbled murrelet nesting habitat on federal lands from Expert Judgment model by province

State/ province[a]	Zone	Not habitat capable	Habitat capable										Total[a]
			Nonreserved					Reserved					
			Unknown	Class 1 (unsuitable)	Class 2 (lower)	Class 3 (moderate)	Class 4 (higher)	Unknown	Class 1 (unsuitable)	Class 2 (lower)	Class 3 (moderate)	Class 4 (higher)	
		Thousand acres											
Washington:													
Olympic Peninsula	1	420.4	4.1	62.1	31.9	9.1	11.7	40.3	245.7	203.4	67.4	432.7	1,108.5
	2	0	0	0	0	0	0	0	0	0	0	0	0
Total		420.4	4.1	62.1	31.9	9.1	11.7	40.3	245.7	203.4	67.4	432.7	1,108.5
Western Lowlands	1	32.1	0	0.3	0.1	0.1	0	3.6	24.9	26.7	23.9	2.4	82.0
	2	0	0	0	0	0	0	0	0	0	0	0	0
Total		32.1	0	0.3	0.1	0.1	0	3.6	24.9	26.7	23.9	2.4	82.0
Western Cascades	1	394.9	4.4	47.1	24.4	4.8	29.0	19.9	149.4	97.5	20.1	224.1	620.5
	2	789.6	1.8	37.4	20.7	3.1	26.5	13.0	109.3	84.6	16.2	195.7	508.4
Total		1,184.5	6.2	84.5	45.1	7.9	55.5	32.9	258.7	182.1	36.2	419.8	1,128.9
Eastern Cascades	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	208.1	1.5	21.1	15.5	0.5	2.1	0.9	13.4	17.7	0.5	2.5	75.7
Total		208.1	1.5	21.1	15.5	0.5	2.1	0.9	13.4	17.7	0.5	2.5	75.7
Washington total		1,845.0	11.9	168.0	92.6	17.5	69.4	77.6	542.8	429.9	127.9	857.5	2,395.1
Oregon:													
Coast Range	1	30.3	2.9	178.0	73.5	19.2	78.6	9.1	404.4	176.4	30.1	376.1	1,348.2
	2	0	0.3	10.5	7.8	1.6	14.3	0	0.8	0.4	0.1	1.3	37.1
Total		30.3	3.3	188.5	81.2	20.7	93.0	9.1	405.2	176.8	30.1	377.5	1,385.3
Klamath	1	26.9	8.3	122.0	38.6	5.5	43.4	41.0	374.3	159.2	22.4	249.6	1,064.4
	2	61.9	11.8	84.0	36.5	7.7	73.3	8.2	61.7	28.4	5.1	58.5	375.1
Total		88.8	20.1	205.9	75.1	13.2	116.7	49.2	436.0	187.6	27.5	308.2	1,439.6
Willamette Valley	1	2.7	0.1	0.9	0.4	0.2	0.1	0.7	1.0	0.5	0.4	0.3	4.6
	2	6.1	0.3	0.4	0.2	0	0.1	0.1	0.2	0.1	0.1	0.1	1.6
Total		8.8	0.4	1.3	0.5	0.3	0.2	0.8	1.2	0.6	0.4	0.4	6.2

Table 5-4—Summary of estimated area of potential marbled murrelet nesting habitat on federal lands from Expert Judgment model by province (continued)

			Habitat capable										
			Nonreserved					Reserved					
State/ province[a]	Zone	Not habitat capable	Unknown	Class 1 (unsuitable)	Class 2 (lower)	Class 3 (moderate)	Class 4 (higher)	Unknown	Class 1 (unsuitable)	Class 2 (lower)	Class 3 (moderate)	Class 4 (higher)	Total[a]
						Thousand acres							
Western													
Cascades	1	0	0	0	0	0	0	0	0.4	0.1	0.1	0.2	0.8
	2	0.1	0.6	25.9	11.1	2.9	3.4	0.2	6.3	1.7	0.5	1.2	53.9
Total		0.1	0.6	25.9	11.1	2.9	3.4	0.2	6.7	1.8	0.6	1.4	54.7
Oregon total		128.0	24.4	421.7	168.0	37.1	213.3	59.3	849.1	366.8	58.7	687.4	2,885.7
California:													
Coast Range	1	109.5	0	2.3	3.5	1.0	5.1	0	26.2	65.0	26.5	91.6	221.2
	2	12.8	0	0.3	0.7	0	0.2	0	0.4	0.7	0	0.6	2.9
Total		122.3	0	2.6	4.2	1.0	5.3	0	26.5	65.7	26.6	92.2	224.1
Klamath	1	180.4	0	40.8	70.6	2.6	46.1	0	67.6	166.6	6.0	171.8	572.1
	2	327.9	0	81.8	84.3	6.4	109.4	0	58.1	71.5	4.4	128.9	544.6
Total		508.3	0	122.6	154.9	9.0	155.5	0	125.7	238.0	10.3	300.6	1,116.6
California Total		630.6	0	125.2	159.1	10.0	160.7	0	152.2	303.7	36.9	392.9	1, 340.7
Plan area total		2,603.6	36.3	714.9	419.8	64.7	443.3	136.9	1,544.0	1,100.4	223.5	1,937.7	6,621.5

[a] Totals computed prior to rounding.

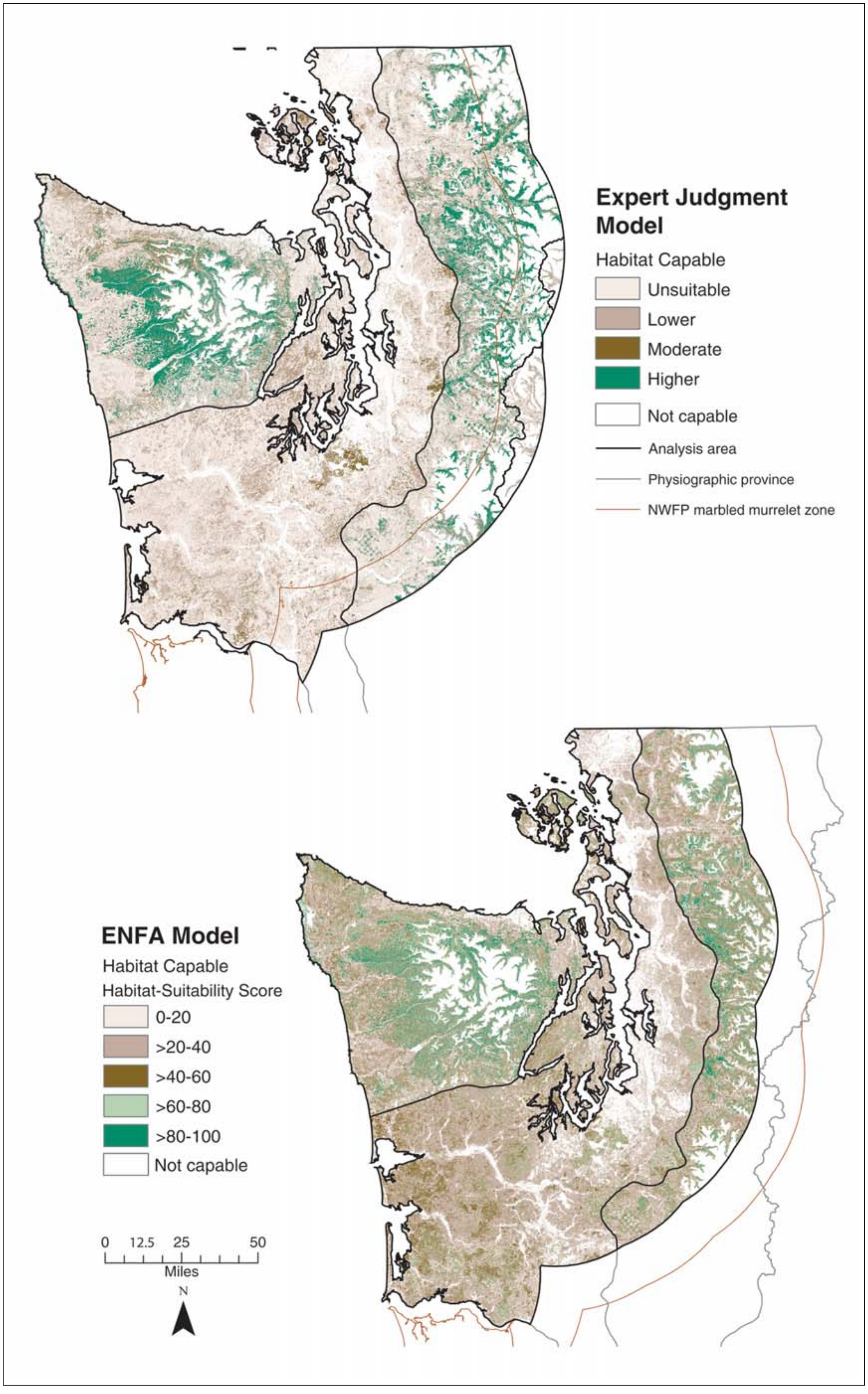


Figure 5-5a—Distribution of classes of habitat from the Expert Judgment model (upper left) and habitat-suitability scores from the Ecological Niche Factor Analysis (ENFA) model (lower right) in Washington. See text for descriptions of techniques and class definitions. NWFP = Northwest Forest Plan.

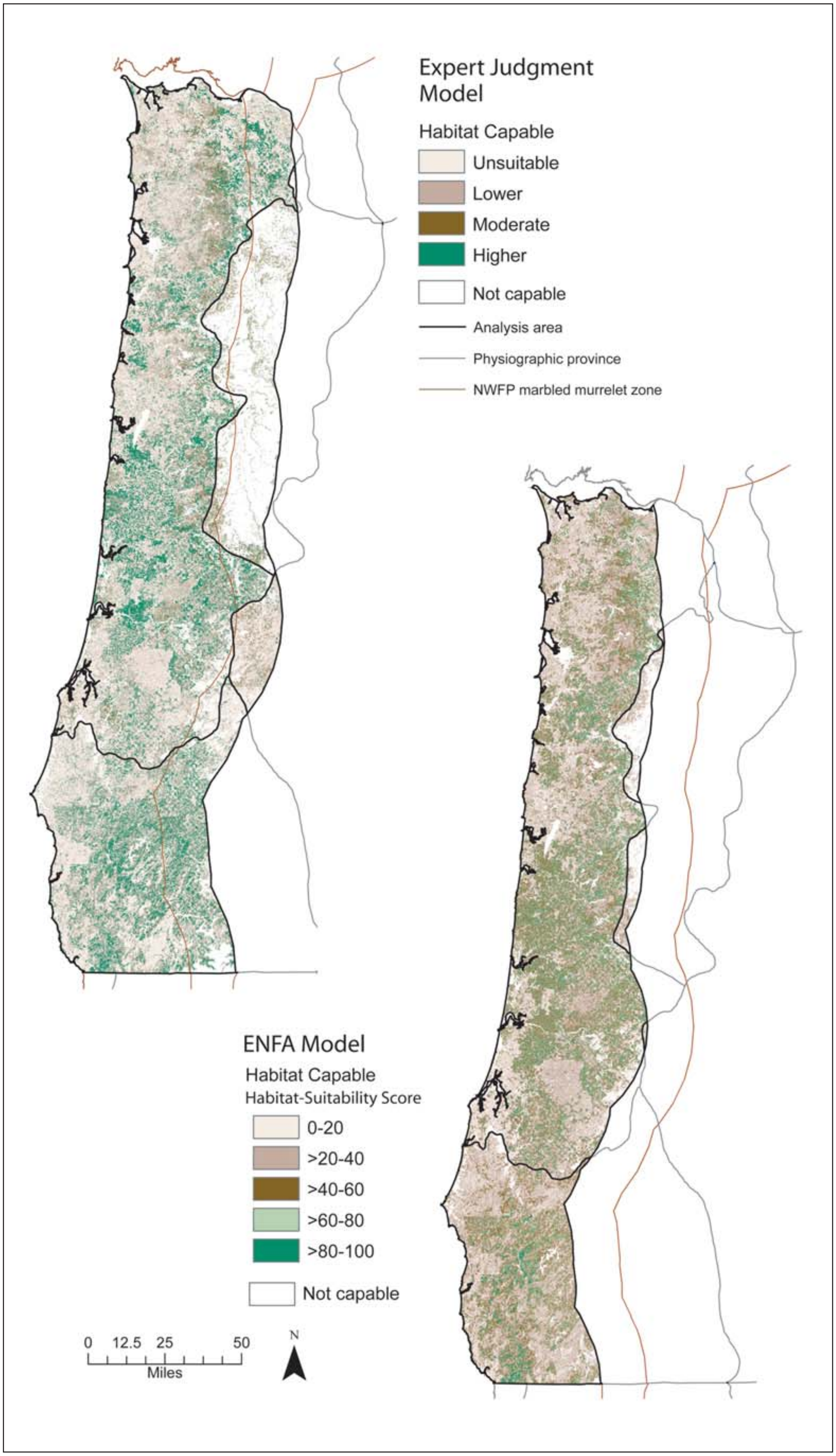


Figure 5-5b—Distribution of classes of habitat from the Expert Judgment model (upper left) and habitat-suitability scores from the Ecological Niche Factor Analysis (ENFA) model (lower right) in Oregon. See text for descriptions of techniques and class definitions. NWFP = Northwest Forest Plan.

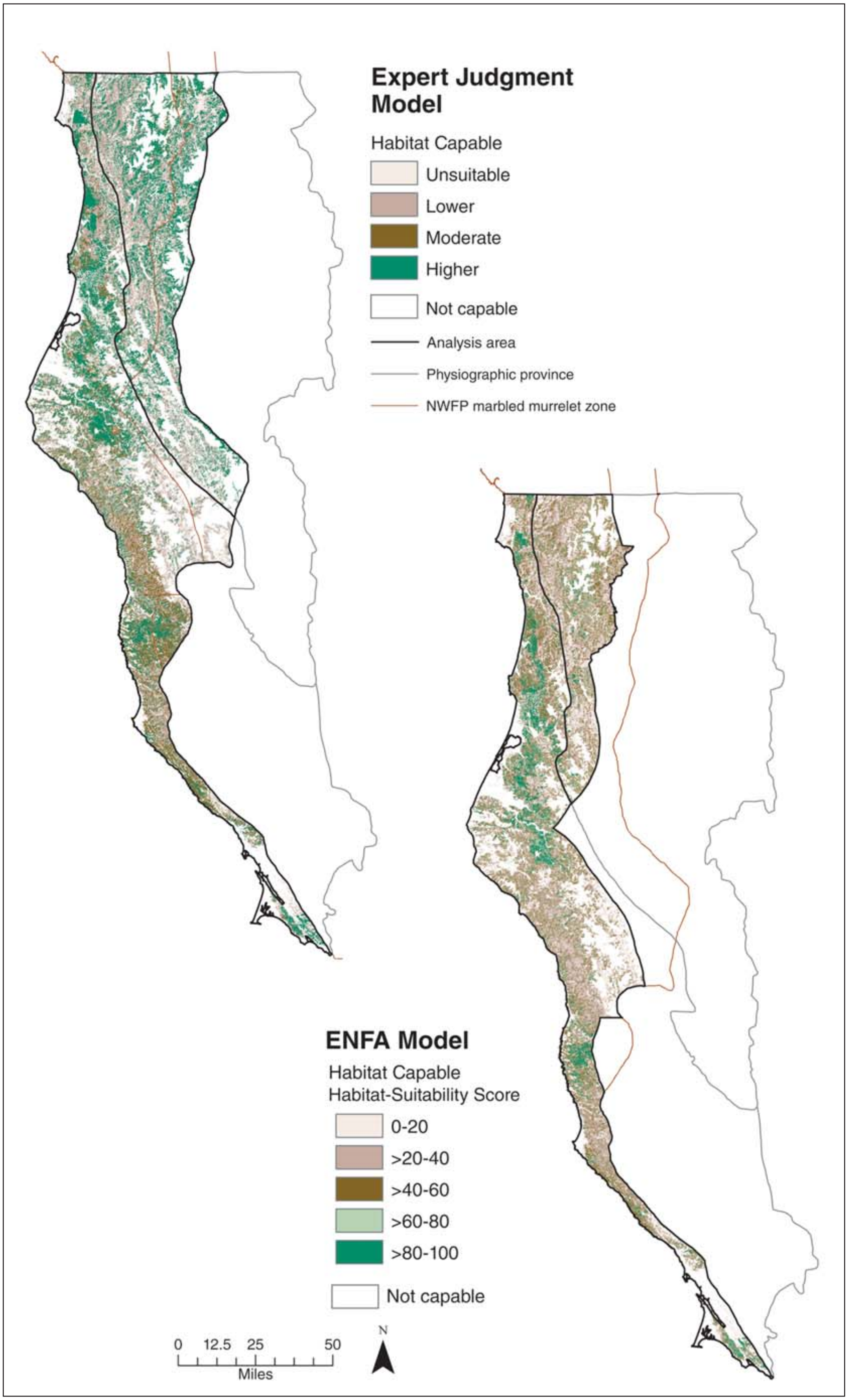


Figure 5-5c—Distribution of classes of habitat from the Expert Judgment model (upper left) and habitat-suitability scores from the Ecological Niche Factor Analysis (ENFA) model (lower right) in California. See text for descriptions of techniques and class definitions. NWFP = Northwest Forest Plan.

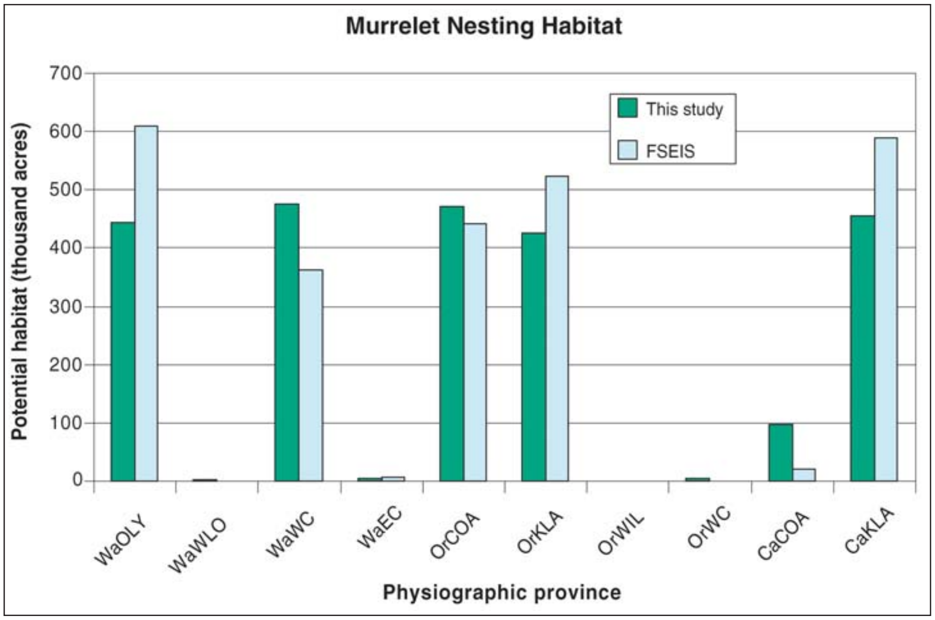


Figure 5-6—Comparison of the amount of potential marbled murrelet nesting habitat on federal land as estimated from our Expert Judgment model (from the highest suitability class) with the amount estimated in the final supplemental environmental impact statement (USDA and USDA 1994a). See figure 5-1 for locations of physiographic provinces. WaOLY = WA Olympic Peninsula, WaWLO = WA Western Lowlands, WaWC = WA Western Cascades, WaEC = WA Eastern Cascades, OrCOA = OR Coast Range, OrKLA = OR Klamath, OrWIL = OR Willamette Valley, OrWC = OR Western Cascades, CaCOA = CA Coast Range, and CaKLA = CA Klamath.

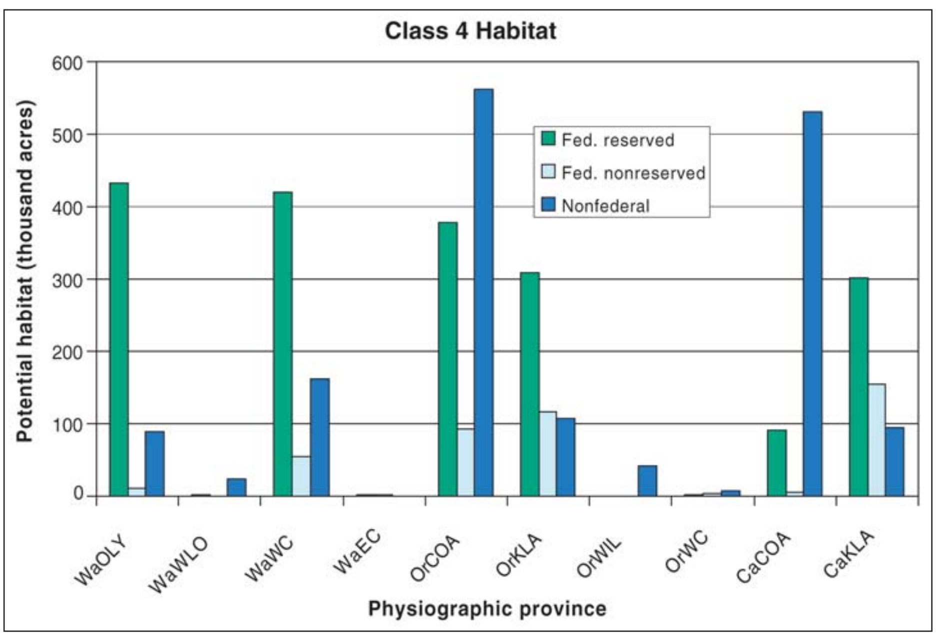


Figure 5-7—Estimated amounts of potential marbled murrelet nesting habitat by province for nonfederal lands, and reserved or nonreserved federal lands. Murrelet conservation Zones 1 and 2 are represented. Habitat estimates are derived from the highest suitability class (class 4) from the Expert Judgment model. See figure 5-1 for locations and figure 5-6 for abbreviations of physiographic provinces.

Table 5-5—Estimated acres of potential marbled murrelet nesting habitat on nonfederal lands from Expert Judgment model by province

State/ province[a]	Zone	Not habitat capable	Habitat capable: Unknown	Class 1 (unsuitable)	Class 2 (lower)	Class 3 (moderate)	Class 4 (higher)	Total[a]
		Thousand acres						
Washington:								
Olympic Peninsula	1	117.5	49.3	910.3	284.2	52.3	88.5	1,384.5
	2	0	0	0	0	0	0	0
Total		117.5	49.3	910.3	284.2	52.3	88.5	1,384.5
Western Lowlands	1	1,487.9	94.6	2810.3	973.2	186.0	22.4	4,086.6
	2	61.7	7.6	195.8	51.8	9.2	1.7	266.1
Total		1,549.6	102.3	3,006.1	1,025.0	195.2	24.1	4,352.7
Western Cascades	1	145.1	50.1	841.5	283.5	42.6	143.4	1,361.1
	2	57.5	8.2	249.5	46.0	7.5	19.0	330.1
Total		202.5	58.3	1,091.0	329.5	50.0	162.4	1,691.2
Eastern Cascades	1	0	0	0	0	0	0	0
	2	24.5	1.4	21.3	7.7	0.4	0.9	31.7
Total		24.5	1.4	21.3	7.7	0.4	0.9	31.7
Washington total		1,894.2	211.2	5,028.7	1,646.4	297.9	275.9	7,460.1
Oregon:								
Coast Range	1	317.9	41.8	2,264.7	575.8	149.3	476.0	3,507.5
	2	96.5	5.3	277.2	51.6	11.0	86.6	431.7
Total		414.5	47.1	2,541.9	627.4	160.2	562.6	3,939.2
Klamath	1	63.6	23.2	482.0	75.8	8.1	53.0	642.1
	2	56.3	24.1	231.3	51.2	9.7	55.2	371.4
Total		119.9	47.3	713.3	127.0	17.8	108.2	1,013.5
Willamette Valley	1	171.3	26.2	57.1	21.2	12.9	12.0	129.4
	2	903.5	48.5	87.2	31.3	22.4	29.5	218.9
Total		1,074.8	74.7	144.3	52.5	35.3	41.5	348.3
Western Cascades	1	0.7	0.1	3.4	0.9	0.3	0.2	4.8
	2	29.2	4.4	154.1	40.5	8.9	7.1	215.1
Total		29.9	4.5	157.5	41.4	9.2	7.3	219.9
Oregon total		1,639.1	173.7	3,557.0	848.2	222.5	719.6	5,521.0
California:								
Coast Range	1	892.7	0	283.7	530.1	313.1	477.4	1,604.3
	2	208.2	0	23.3	74.1	46.7	52.7	196.9
Total		1,100.9	0	307.0	604.3	359.9	530.1	1,801.2
Klamath	1	61.2	0	73.9	99.0	6.5	61.4	240.9
	2	101.1	0	41.0	49.7	3.4	33.8	127.9
Total		162.3	0	114.9	148.7	9.9	95.2	368.8
California total		1,263.2	0	421.9	753.0	369.8	625.3	2,170.0
Plan area total		4,796.4	384.9	9,007.6	3,247.6	890.2	1,620.8	15,151.1

[a] Totals were computed prior to rounding.

Table 5-6—Percentage of potential higher quality nesting habitat on all lands (federal and nonfederal) in patches >500 acres and patches >1,000 acres

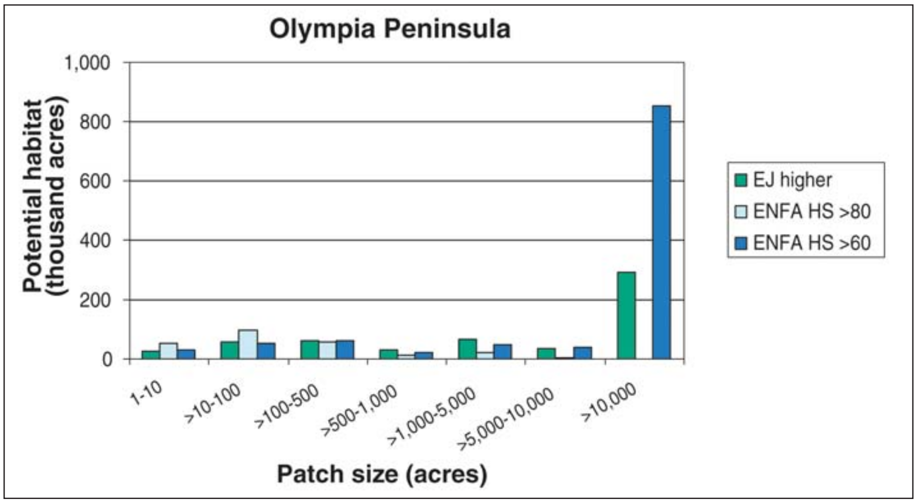
	Expert Judgment[a]		ENFA HS >80[b]		ENFA HS >60[c]	
Province	**>500**	**>1,000**	**>500**	**>1,000**	**>500**	**>1,000**
Washington:						
Olympic Peninsula	75	69	16	11	87	85
Western Lowlands	0	0	0	0	37	30
Western Cascades	69	60	15	11	79	73
Eastern Cascades	0	0	NA[d]	NA	NA	NA
Oregon:						
Coast Range	52	43	<1	0	67	58
Klamath	56	48	23	9	54	44
Willamette Valley	0	0	0	0	0	0
Western Cascades	0	0	0	0	0	0
California:						
Coast Range	54	47	51	45	60	54
Klamath	64	51	3	0	37	24

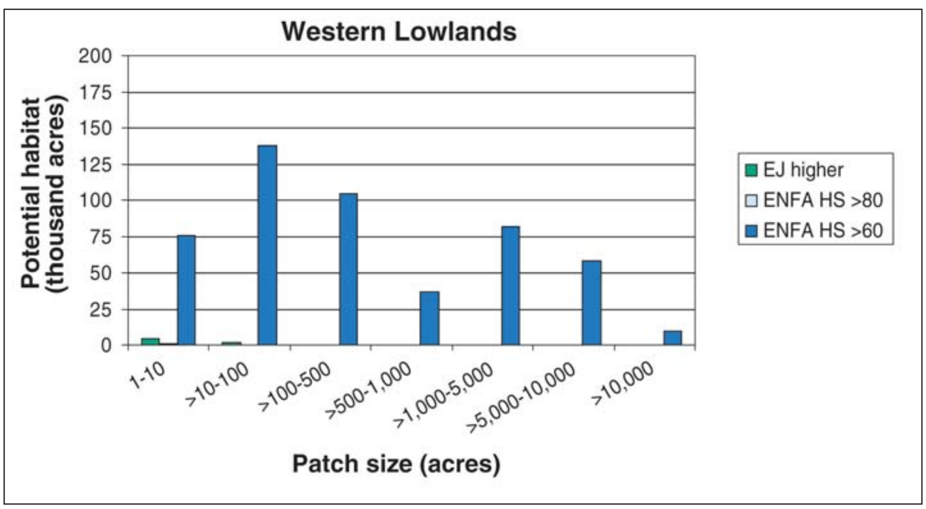
[a] Expert Judgment model with habitat defined as higher quality habitat (class 4 in table 5-1) in marbled murrelet Zones 1 and 2.

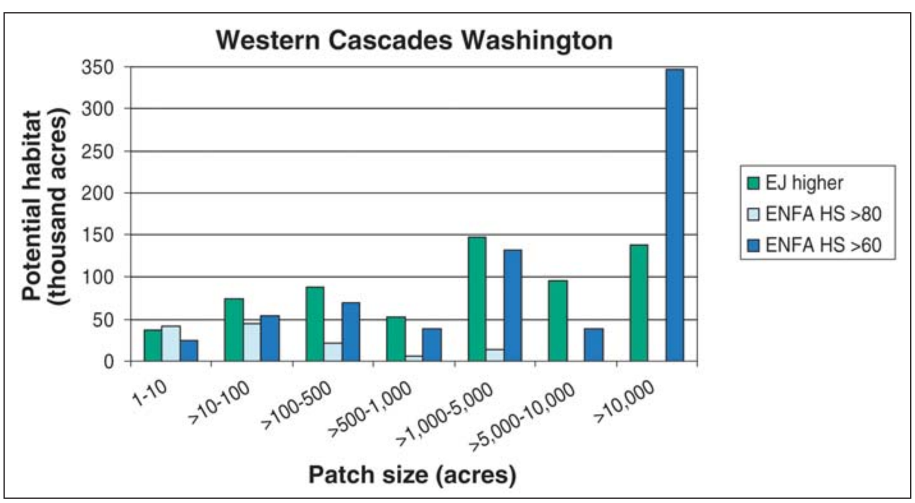
[b] Ecological Niche Factor Analysis with habitat (ENFA) defined by using habitat-suitability (HS) scores >80 in marbled murrelet Zone 1.

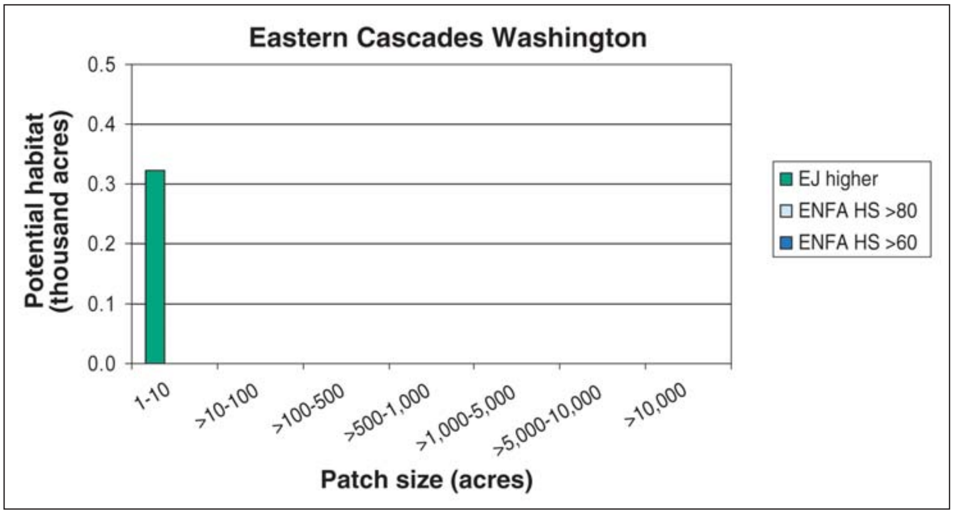
[c] Ecological Niche Factor Analysis with habitat defined by using HS scores >60 in marbled murrelet Zone 1.

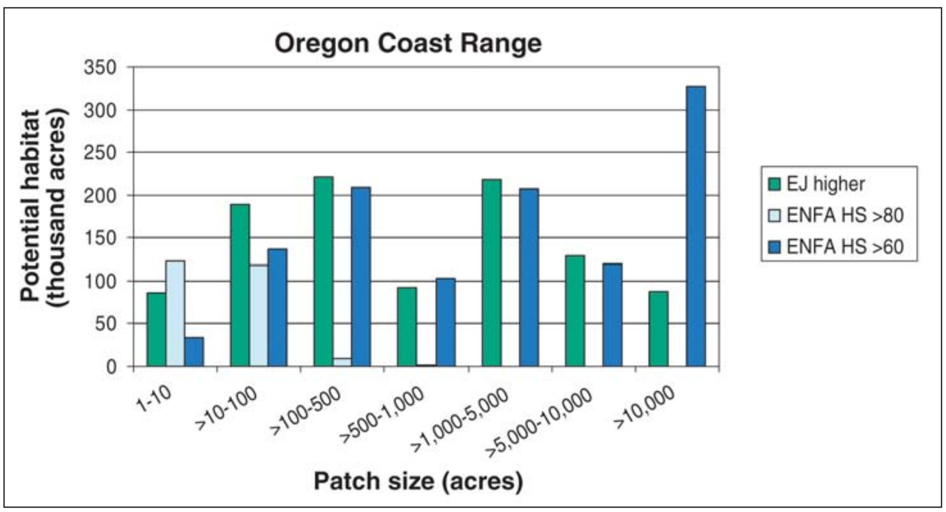
[d] NA = not applicable; marbled murrelet Zone 1 does not extend to this province.

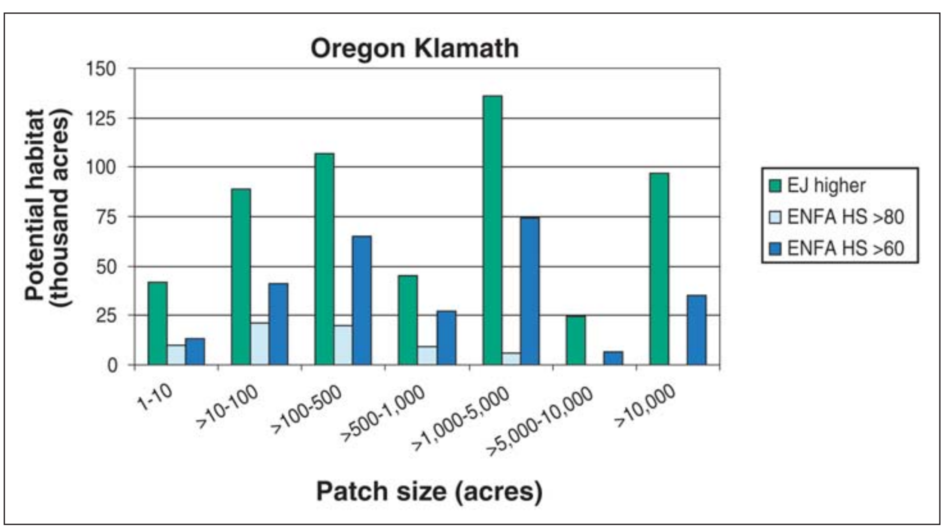

Olympia Peninsula
Potential habitat (thousand acres)
1,000
800
600
400
200
0
1-10
>10-100
>100-500
>500-1,000
>1,000-5,000
>5,000-10,000
>10,000
Patch size (acres)
EJ higher
ENFA HS >80
ENFA HS >60

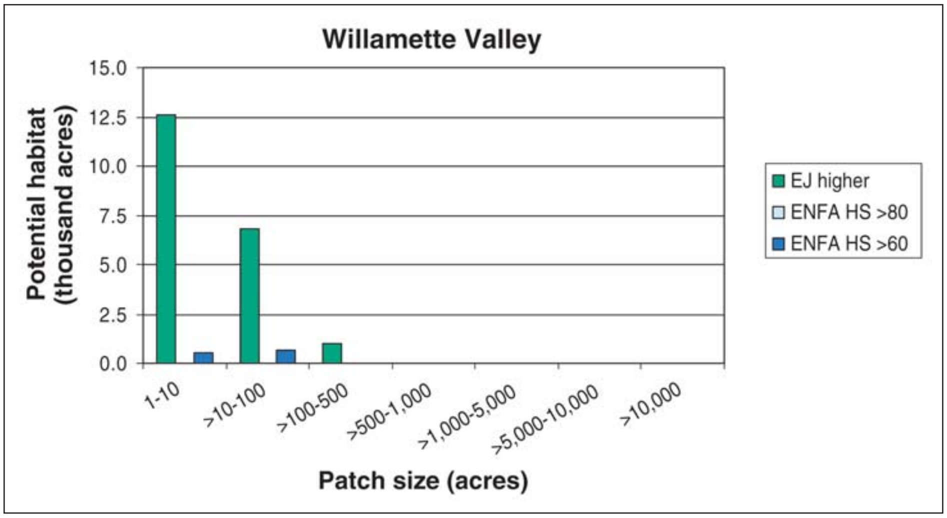

Western Lowlands
Potential habitat (thousand acres)
200
175
150
125
100
75
50
25
0
1-10
>10-100
>100-500
>500-1,000
>1,000-5,000
>5,000-10,000
>10,000
Patch size (acres)
EJ higher
ENFA HS >80
ENFA HS >60

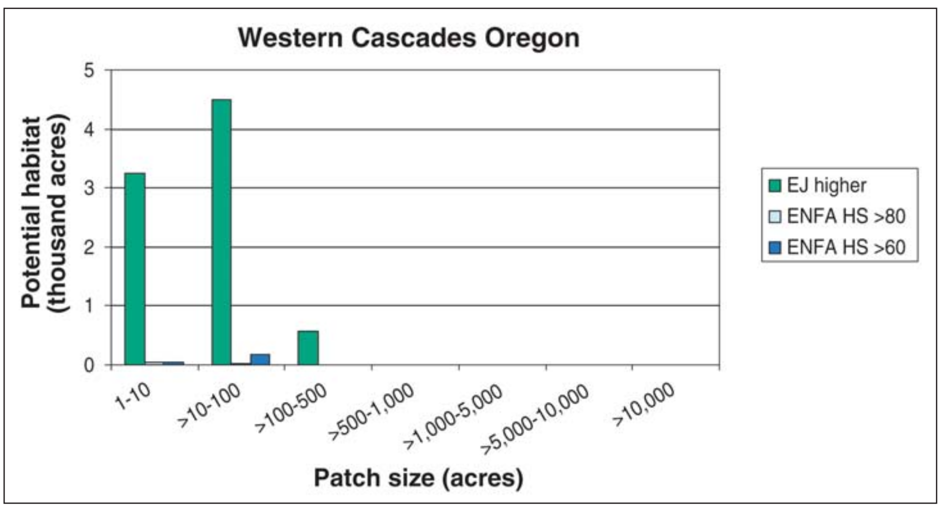

Western Cascades Washington
Potential habitat (thousand acres)
350
300
250
200
150
100
50
0
1-10
>10-100
>100-500
>500-1,000
>1,000-5,000
>5,000-10,000
>10,000
Patch size (acres)
EJ higher
ENFA HS >80
ENFA HS >60

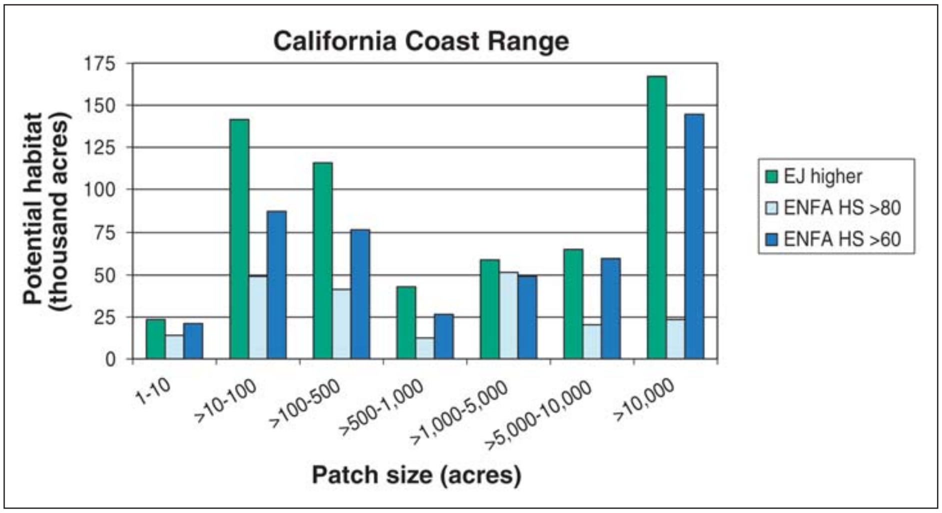

Eastern Cascades Washington
Potential habitat (thousand acres)
0.5
0.4
0.3
0.2
0.1
0.0
1-10
>10-100
>100-500
>500-1,000
>1,000-5,000
>5,000-10,000
>10,000
Patch size (acres)
EJ higher
ENFA HS >80
ENFA HS >60


Oregon Coast Range
Potential habitat (thousand acres)
350
300
250
200
150
100
50
0
1-10
>10-100
>100-500
>500-1,000
>1,000-5,000
>5,000-10,000
>10,000
Patch size (acres)
EJ higher
ENFA HS >80
ENFA HS >60


Oregon Klamath
Potential habitat (thousand acres)
150
125
100
75
50
25
0
1-10
>10-100
>100-500
>500-1,000
>1,000-5,000
>5,000-10,000
>10,000
Patch size (acres)
EJ higher
ENFA HS >80
ENFA HS >60


Willamette Valley
Potential habitat (thousand acres)
15.0
12.5
10.0
7.5
5.0
2.5
0.0
1-10
>10-100
>100-500
>500-1,000
>1,000-5,000
>5,000-10,000
>10,000
Patch size (acres)
EJ higher
ENFA HS >80
ENFA HS >60


Western Cascades Oregon
Potential habitat (thousand acres)
5
4
3
2
1
0
1-10
>10-100
>100-500
>500-1,000
>1,000-5,000
>5,000-10,000
>10,000
Patch size (acres)
EJ higher
ENFA HS >80
ENFA HS >60



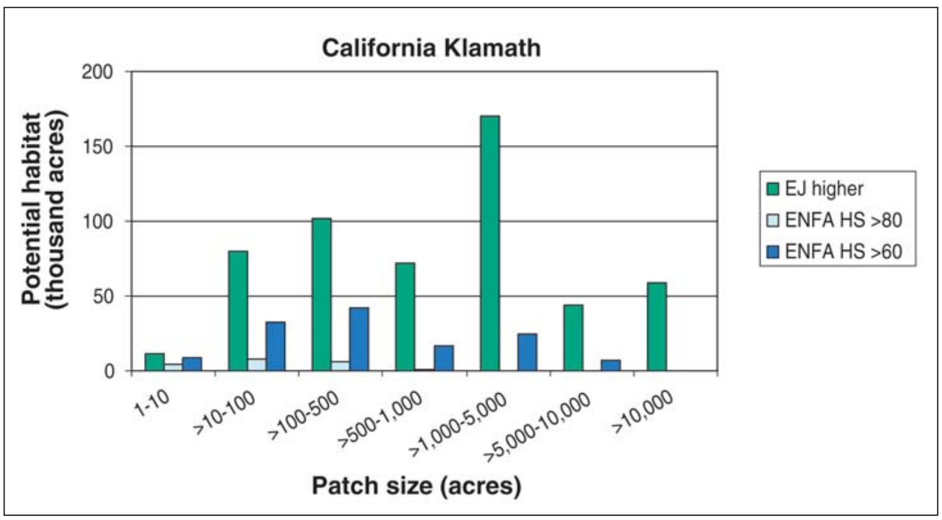


Figure 5-8—Area of potential marbled murrelet nesting habitat in relation to size of patch in each physiographic province. Habitat was classified by using two modeling approaches, Expert Judgment (EJ) and Ecological Niche Factor Analysis (ENFA). HS = habitat suitability. See text for details.

Habitat Change

To account for changes to habitat over the 10 years since the Plan was implemented, we overlaid the disturbance data with our Expert Judgment model to compute how much has been lost because of fire or harvest. Across all provinces, a total of 55,500 acres (2.3 percent) of class 4 habitat has been lost on federal lands owing to fire and harvest. Losses on nonfederal lands were greater, totaling 139,700 acres (8.6 percent). Losses on federal lands were due primarily to fire (95 percent of all losses), whereas losses on nonfederal lands were due primarily to harvest (nearly 100 percent). Losses are small at the provincial or regional level but may have great impact at the local scale. The Biscuit Fire (Azuma et al. 2004), for example, burned over 40,000 acres of class 4 habitat in one area of the Oregon Klamath province.

These disturbances also reduced the size of habitat patches. Figure 5-9 shows that the amount of class 4 habitat was reduced in nearly every class of patch size, with the greatest declines in the largest patches. Most of this decline occurred in the Oregon Klamath, again because of the large Biscuit Fire. Patch size became smaller over the past 10 years owing to disturbance, but we expect patch sizes to increase once currently younger forest matures and becomes class 4 habitat. This process should result in larger patch sizes in the LSRs.

We investigated the degree to which class 4 habitat might accrue as currently unsuitable habitat within reserves matures. Moeur (see footnote 3) computed an average net annual transition from smaller diameter forest to larger diameter forest structure (i.e., from forests with <30 in QMD to forests with 30 in or larger QMD) within the murrelet range of about 4 percent per decade. If we assume this rate applies to murrelet habitat on federal lands, we estimate a net decadal increase of about 95,300 acres of larger diameter forest over and above losses from fire and harvest. We do not know, however, how much of this larger diameter forest is actually suitable for nesting by murrelets.

Over the long run, that is, over the next 100 years or more, we can also estimate the potential for habitat recovery from data in table 5-4. Habitat-capable acres that are in LSRs (not including LSR 3 or LSR 4) and are classified as unknown, unsuitable, lower suitability or moderate suitability may, given enough time, become more highly suitable habitat. We focus on only LSRs for two reasons: (1) young forest in LSRs is expected to mature and is not subject to harvest, and (2) we assume young forest on congressionally reserved lands has resulted from natural disturbances so the amount of young forest is likely to persist. Therefore, if we add up those acres in the lower suitability classes within LSRs, we can get a rough estimate of long-term potential habitat recovery. Across all provinces, there are about 2.8 million habitat-capable forest acres that occur within LSRs. Of this, we classified 36 percent, or about 1.0 million acres, as higher suitability (class 4) habitat. The remainder (63 percent of habitat-capable acres) has some potential to become higher suitability habitat. If all of these acres become habitat, we might project a potential increase of as much as 1.7 million acres of habitat over the next 100 years (or 170,000 acres per decade). Not all currently unsuitable acres will become habitat, but if even half of those acres eventually become suitable then we might still project an increase of 850,000 additional acres over the next 100 years (or 85,000 acres per decade). Recall that observed losses of class 4 habitat to fire and harvest were 55,500 acres on federal lands over the last decade, so it seems reasonable that we will observe a net increase in suitable habitat over time. The questions we cannot resolve are how long this recovery process might actually take, what proportion of currently unsuitable forest will eventually attain suitable status, and whether marbled murrelets will find and colonize newly created nesting habitat. However, if the transition rates that have been observed continue, it does appear there will be a net increase in suitable murrelet nesting habitat over time. We recognize, however, that increased fuel loadings in drier portions of the range could lead to higher risk of catastrophic loss owing to fire without more aggressive fuels management. For this reason, there is considerable uncertainty in the likelihood of future habitat losses.

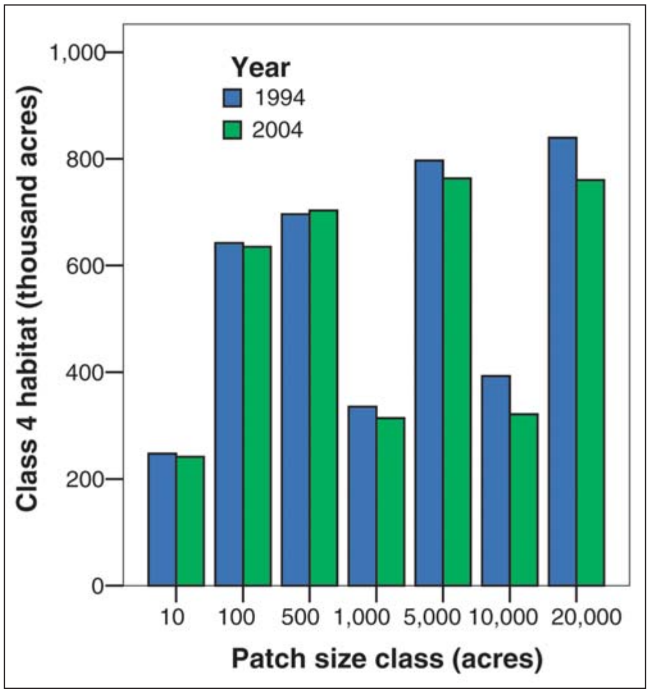


Figure 5-9—Area of class 4 habitat (as estimated by using the Expert Judgment model) in 1994 and 2004 by patch size class, pooled over all provinces. Values of patch size indicate upper limit of ranges for each class.

Model Validation

To evaluate the utility of our Expert Judgment model, we compared the frequency distribution of each of the habitat suitability classes among occupied polygons, active nests, and the rangewide average over all lands (fig. 5-10). Across the murrelet range, most habitat-capable land (52 percent) is classified as class 1 (lower suitability) habitat, and 18 percent is classified as class 4 (higher suitability) habitat. In contrast, both occupied polygons and active nest sites are dominated by class 4 habitat (57 and 60 percent, respectively, for occupied polygons and nest sites). Results differ by province, but overall, these patterns suggest there is utility in the Expert Judgment model. If nest sites differed markedly from occupied polygons or if there was little difference between habitat suitability within occupied polygons and available sites, we would have less confidence in our results.

ENFA Model Results

Baseline Habitat

We completed ENFA habitat suitability models (by using BioMapper) for all the area represented in marbled murrelet Zone 1 (figs. 5-5a through 5-5c), covering nine physiographic provinces. Models for all areas showed that murrelets were observed at locations that differed from average condi-tions in the respective provinces (based on marginality scores, table 5-7; also see table 5-3 to compare species and global means for each variable). Tolerance scores ranged from 0.61 in Southern Oregon-California to 0.66 in Washington, indicating that the range or variance in habitat conditions where murrelets occur differed from those of the provinces (table 5-7). Across all areas, varibles that had the strongest influence on habitat suitability were QMD, interaction of QMD and conifer cover, conifer cover, the two landscape variables (PATCH8 and PCTHIKB), and structure. The two landscape variables were among the top variables in factor 1 (marginality) in all three areas (table 5-8).

Acreages of habitat are not comparable to those from the FSEIS because the FSEIS did not distinguish habitat in marbled murrelet Zones 1 and 2. Estimates from the ENFA models (tables 5-9 and 5-10) are also not easily compared with estimates from our Expert Judgment model because it is not clear what threshold from the habitat suitability ranking to use. We believe it is best to consider a range of HS scores to bracket a range of assumptions about what threshold is best. We have elected to display HS scores greater than 60 (HS >60) as a “generous” portrayal of potential nesting habitat and a threshold of greater than 80 (HS >80) as a more conservative estimate (fig. 5-11).

Under the HS >60 definition, we estimate 4.0 million acres of potential habitat on all ownerships in marbled murrelet Zone 1 and 1.1 million acres under the HS >80 definition. In the same area, on federal lands, we estimate 1.9 million acres of habitat under the HS >60 definition and 0.6 million acres under the HS >80 definition. Under both

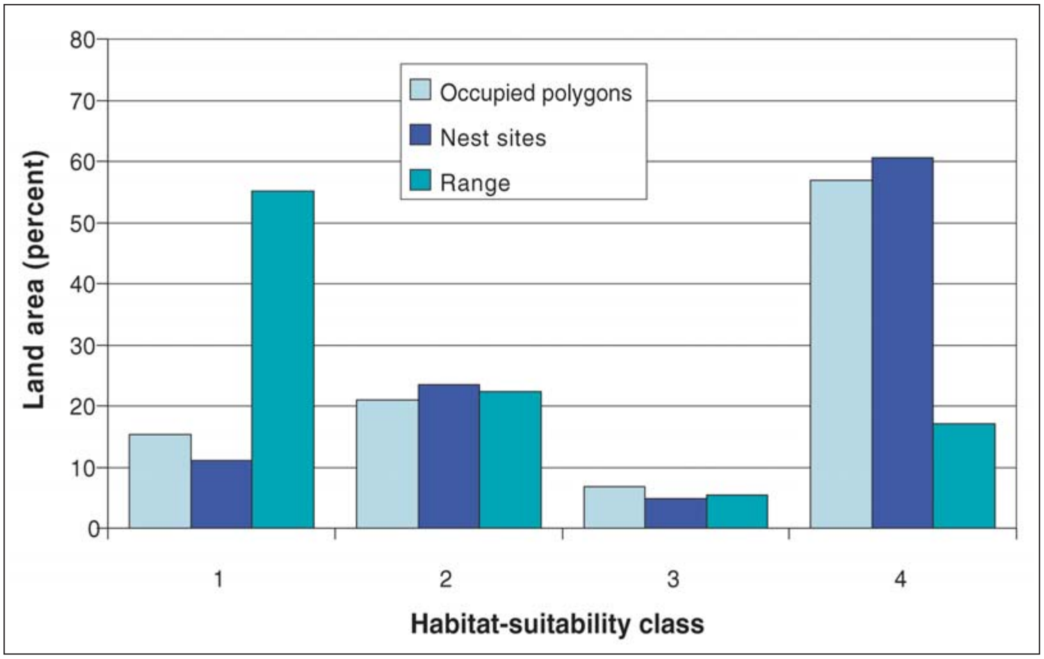


Figure 5-10—Frequency distributions of habitat-suitability classes for all habitat capable lands within murrelet Zone 1 (range), for occupied polygons, and for active nest sites. Habitat-suitability classes are defined by using the Expert Judgment model following criteria in table 5-1.

Table 5-7—Summary statistics from Ecological Niche Factor Analysis by using BioMapper for each analysis area[a]

Analysis area	Marginality [b]	Specialization [c]	Tolerance [d]	Spearman correlation[e]	CV [f]
Washington	1.34	1.53	0.66	0.99	5.27
Northern Oregon	1.10	1.60	0.63	1.00	7.49
Southern Oregon/California	1.38	1.65	0.61	0.98	4.10

[a] See text for definitions and interpretations of summary statistics

[b] Index of difference between means of environmental variables at occupied polygons and of the entire analysis area.

[c] Index of difference between variance of environmental variables at occupied polygons and of the entire analysis area.

[d] Index of difference between variance of environmental variables at occupied polygons and of the entire analysis area, scaled between 0 and 1.0.

[e] Correlation from *k*-fold cross validation (see text for details).

[f] Coefficient of variation from *k*-fold cross validation (see text for details).

Table 5-8—Factor 1 through 4 scores (factor loadings) from Ecological Niche Factor Analysis using BioMapper for marbled murrelet Zone 1 by analysis area[a]

Variable[b]	Factor 1 (15%)	Factor 2 (24%)	Factor 3 (17%)	Factor 4 (13%)
	Washington			
PATCH8	0.50	0.00	-0.02	0.02
PCTHIKB	0.36	0.00	-0.10	0.57
BDLF10	-0.27	-0.02	0.34	0.28
CONIF10	0.28	0.28	0.70	0.42
QMD	0.41	0.55	0.27	0.15
CONIF10*QMD	0.39	-0.78	-0.55	-0.26
STRUCTURE	0.35	0.00	0.10	-0.58
SLOPE	0.04	0.00	0.01	0.00
SOLAR	-0.11	0.01	-0.03	0.06
TOSEA	0.08	0.00	0.04	-0.03
	Northern Oregon			
	Factor 1 (21%)	**Factor 2 (23%)**	**Factor 3 (17%)**	**Factor 4 (14%)**
PATCH8	0.46	0.00	0.00	0.10
PCTHIKB	0.46	-0.09	0.06	-0.49
BDLF10	-0.08	0.09	-0.19	-0.09
CONIF10	0.21	-0.14	-0.53	-0.40
QMD	0.38	-0.58	-0.45	-0.16
CONIF10*QMD	0.37	0.79	0.69	0.33
STRUCTURE	0.42	0.01	-0.02	0.07
SLOPE	0.14	-0.01	0.00	0.15
SOLAR	-0.07	-0.02	0.01	0.05
TOSEA	-0.23	0.01	0.01	-0.65
	Southern Oregon/California			
	Factor 1 (16%)	**Factor 2 (21%)**	**Factor 3 (18%)**	**Factor 4 (14%)**
PATCH8	0.41	0.00	0.01	-0.10
PCTHIKB	0.41	0.16	0.05	0.68
BDLF10	-0.20	0.10	0.14	0.07
CONIF10	0.27	0.03	0.50	-0.26
QMD	0.44	-0.50	0.43	-0.28
CONIF10*QMD	0.40	0.70	-0.73	0.40
STRUCTURE	0.33	-0.46	-0.09	-0.28
SLOPE	-0.09	-0.04	0.01	0.22
SOLAR	0.11	0.02	0.00	-0.09
TOSEA	-0.25	-0.13	-0.01	0.29

[a] Percentages following factor labels indicate the amount of explained variance associated with that factor. Factor 1 is a measure of marginality; Factors 2 through 4 are measures of specialization. Signs are not relevant for factors 2-4; absolute values indicate relative strengths of contributions.

[b] See table 5-2 for variable definitions.

Table 5-9—Estimated acres of potential marbled murrelet nesting habitat on federal lands from Ecological Niche Factor Analysis for marbled murrelet Zone 1 by province

		Habitat capable												
		Nonreserved						Reserved						
			Habitat-suitability score						Habitat-suitability score					
State/ province[a]	Not habitat capable	Unknown	0-20	>20-40	>40-60	>60-80	>80-100	Unknown	0-20	>20-40	>40-60	>60-80	>80-100	Total[a]
								Thousand acres						
Washington:														
Olympic Peninsula	420.4	5.0	18.0	33.5	20.8	33.3	8.3	45.1	51.2	131.8	129.1	417.8	214.6	1,108.5
Western Lowlands	32.1	0	0.0	0.3	0.0	0.2	0.0	4.8	11.6	21.1	18.2	25.7	0.0	82.0
Western Cascades	394.9	5.3	12.6	28.3	20.0	33.2	10.3	23.5	38.7	96.9	83.0	199.2	69.7	620.5
Washington total	847.4	10.3	30.6	62.1	40.9	66.7	18.6	73.4	101.5	249.8	230.2	642.6	284.3	1,811.1
Oregon:														
Coast Range	30.3	0.3	63.4	128.7	64.1	60.0	32.4	14.5	106.8	248.1	229.9	255.8	144.1	1,348.2
Klamath	26.9	8.4	49.9	90.4	38.3	24.2	6.7	42.2	138.5	292.0	171.7	140.4	61.6	1,064.4
Willamette Valley	2.7	0.2	0.5	0.8	0.1	0.0	0.0	0.9	0.7	1.1	0.2	0	0.0	4.6
Western Cascades	0	0	0	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.1	0.1	0.1	0.8
Oregon total	59.9	8.9	113.8	220.0	102.6	84.2	39.1	57.6	246.2	541.5	401.9	396.4	205.7	2,418.0
California:														
Coast Range	109.7	0	1.5	4.4	2.1	1.2	2.6	0.0	24.9	63.7	48.0	31.3	41.2	220.9
Klamath	180.6	0	39.5	74.0	32.8	12.1	1.6	0.0	75.0	151.6	98.7	73.2	13.3	571.8
California total	290.3	0	41.1	78.4	34.9	13.3	4.2	0.0	99.9	215.3	146.7	104.5	54.5	792.7
Plan area total	1,197.6	19.2	185.5	360.5	178.3	164.2	61.9	131.0	447.6	1,006.6	778.9	1,143.5	544.5	5,021.7

[a] Totals were computed prior to rounding.

Table 5-10—Estimated acres of potential marbled murrelet nesting habitat on nonfederal lands from Ecological Niche Factor Analysis for marbled murrelet Zone 1 by province

State/ Province[a]	Not habitat capable	Habitat capable						
		Habitat-suitability score						
		Unknown	0-20	>20-40	>40-60	>60-80	>80-100	Total[a]
		Thousand acres						
Washington:								
Olympic Peninsula	117.5	83.5	322.1	483.8	200.4	241.0	53.6	1,384.5
Western Lowlands	1,487.9	134.7	785.7	2,033.8	631.4	499.1	1.9	4,086.6
Western Cascades	145.1	74.7	236.6	505.4	192.9	269.2	82.3	1,361.1
Washington total	1,750.4	292.9	1,344.5	3,023.0	1,024.8	1,009.2	137.9	6,832.2
Oregon:								
Coast Range	317.9	60.4	1,237.5	1,289.7	401.2	334.1	184.6	3,507.6
Klamath	63.6	23.3	249.8	295.5	53.8	15.2	4.5	642.1
Willamette Valley	171.3	35.8	31.5	55.5	5.3	1.4	0.1	129.4
Western Cascades	0.7	0.1	3.1	1.4	0.1	0.0	0.0	4.8
Oregon total	553.6	119.6	1,521.9	1,642.1	460.4	350.7	189.2	4,283.9
California:								
Coast Range	893.5	0	253.5	619.5	344.5	218.9	167.0	1,603.4
Klamath	61.3	0	80.3	86.9	39.4	25.5	8.5	240.7
California total	954.8	0	333.8	706.4	383.9	244.4	175.5	1,844.0
Plan area total	3,258.8	412.5	3,200.2	5,371.4	1,869.1	1,604.3	502.6	12,960.2

[a] Totals were computed prior to rounding.

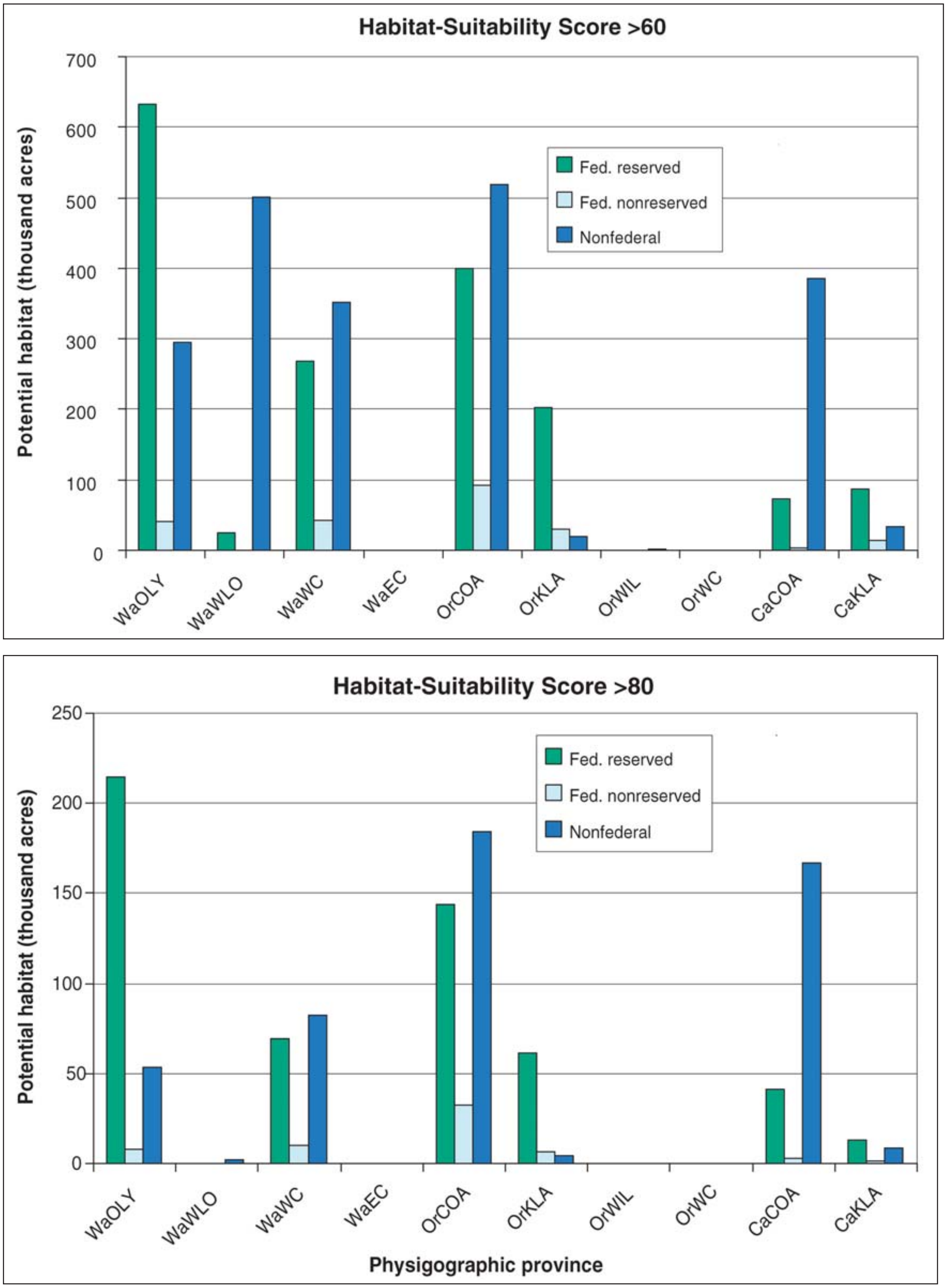


Figure 5-11—Potential marbled murrelet nesting habitat by province for nonfederal lands, and reserved or nonreserved federal lands as estimated from Ecological Niche Factor Analysis. Upper figure shows amounts with habitat-suitability scores >60; lower figure shows amounts with suitability scores >80. All estimates apply only to marbled murrelet Zone 1. See figure 5-1 for locations and figure 5-6 for abbreviations of physiographic provinces.

the HS >60 and HS >80 definitions, three provinces (Olympic Peninsula, Oregon Klamath, and California Klamath) have higher percentages of existing potential habitat on federal lands than nonfederal lands. The Western Lowlands, Oregon Coast Range, and California Coast Range make the largest contributions of nonfederal habitat under the HS >60 definition; the Oregon Coast Range and California Coast Range do so under the HS >80 definition (fig. 5-11, tables 5-9 and 5-10). This is in sharp contrast to the Expert Judgment model, which showed relatively little nonfederal habitat in the Western Lowlands, even though there are many occupied polygons in that province.

Under either definition, we find, as we did for the Expert Judgment model, that most potential nesting habitat on federal land is in the reserved allocations (88 percent for HS >60, 90 percent for HS >80). If we compare these two thresholds against the Expert Judgment model results for federal lands in murrelet Zone 1 (fig. 5-12), we see that acres with HS scores greater than 60 exceed those estimated from the Expert Judgment model in the Olympic Peninsula, Western Lowlands, Western Cascades of Washington, and Oregon Coast Range provinces. Acres with suitability scores greater than 80 are much fewer in all provinces.

Patch Area

Amounts of potential nesting habitat that occurred in larger patches differed among provinces, but also differed depending on how habitat is defined (i.e., using HS >60 or HS >80). For example, percentages of total habitat in patches >1,000 acres were low (11 percent) on the Olympic Peninsula by using the HS >80 model but much higher (85 percent under the HS >60 model (table 5-6). Percentages of habitat in large patches were less than 25 percent in all provinces except the California Coast Range by using the HS >80 model; by using the HS >60 model, percentages exceeded 25 percent in six provinces (table 5-6).

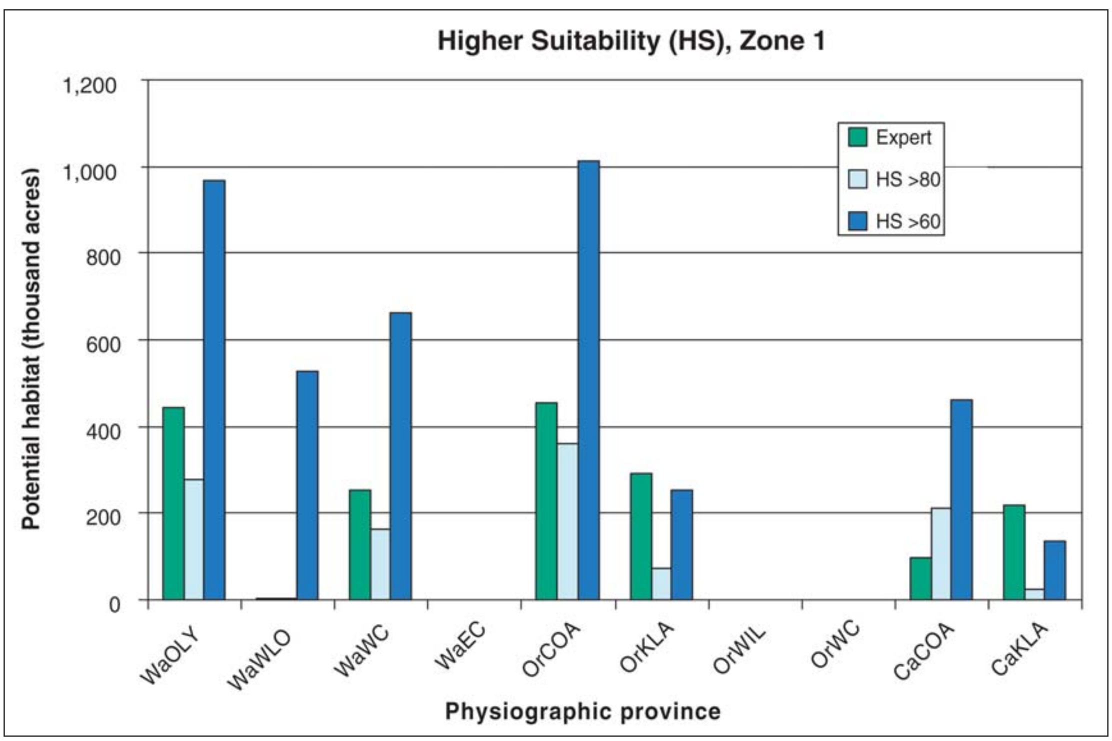


Figure 5-12—Potential marbled murrelet nesting habitat for federal lands for the Expert Judgment model (acres classified as class 4 habitat suitability) and for the Ecological Niche Factor Analysis (ENFA) model (acres classified by using suitability scores >60 and >80) for marbled murrelet Zone 1. The WA Eastern Cascades was omitted from ENFA as marbled murrelet Zone 1 does not occur in that province. See figure 5-1 for locations and figure 5-6 for abbreviations of physiographic provinces.

Habitat Change

We used the techniques described under the Expert Judgment model to estimate habitat losses owing to fire and harvest. On federal lands, there was an estimated loss of 5,500 acres of habitat as defined by HS scores >80 (0.9 percent of total federal habitat) and a loss of 30,000 acres of habitat with HS scores of >60 (1.6 percent). On nonfederal lands, the rate of loss (almost all owing to harvest) was greater, estimated as 55,000 acres (11.0 percent) and 248,800 acres (11.8 percent) for HS >80 and HS >60, respectively. We were unable to compute changes in patch size by using BioMapper for this report. We will do so in subsequent analyses.

Projecting potential growth of habitat when habitat suitability is estimated from the ENFA model is problematic. Unlike the Expert Judgment model, which was based strictly on vegetation attributes, the ENFA model has a mixture of physiographic (slope, index of solar radiation, and distance to sea) and vegetation variables. The physiographic variables will not change over time, so projecting vegetation change would require simulation of QMD, conifer cover, and the other vegetation attributes into the future while holding the physiographic attributes constant and then rerunning the BioMapper analysis with the new values. Such an analysis can be done but is beyond the scope of this report.

Model Validation

We validated the ENFA model in two ways: k-fold cross validation and comparison with actual nests. The k-fold cross validation yielded strong Spearman rank correlations, and relatively low coefficients of variation (table 5-7) indicated good model performance. Estimates of habitat suitability scores at actual nest sites (fig. 5-13) averaged 72.9, 68.0, and 74.5 in Washington, Oregon, and California, respectively. These averages were similar to those computed for the occupied polygons, which were 66.1, 62.4, and 74.6 in the three states. The frequency distribution of suitability scores at the sample of nest sites showed that 72 percent of the nest sites had scores >60 (fig. 5-14). These results give us added confidence that HS scores >60 are a reasonable representation of nesting habitat for the murrelet.

Sources of Uncertainty

This work represents the first attempt to create a rangewide map of potential murrelet nesting habitat from consistent baseline vegetation information. We believe the effort has resulted in an improved understanding of the current amount and distribution of nesting habitat compared to the information available at the time of the FEMAT report and subsequent FSEIS (FEMAT 1993, USDA and USDI 1994a). There are, however, a number of sources of uncertainty that should be recognized.

Vegetation Mapping

First, there is uncertainty and error in the underlying vegetation classification. We have previously discussed accuracy assessment information for the vegetation data (see methods above). Error rates in the original vegetation attributes such as QMD and cover varied with the size of classes analyzed. For example, the overall accuracy for the classes we used (table 5-2) was 44.5 percent over all lands on the Olympic Peninsula province (Moeur et al. 2005). We used 10-percent intervals for canopy cover, but the accuracy assessment was reported for intervals of 20 percent. For the 20-percent intervals, overall accuracy was 64.6 percent; we expect accuracy would be poorer for the 10-percent intervals that we used. Interpolating from Moeur et al. (2005, app. 5), we estimate an accuracy of about 42 percent for 10-percent intervals.

Resolution is also a source of uncertainty. As previously mentioned, both spatial and attribute resolution differed between the two primary vegetation data sets, IVMP and CALVEG. In general, finer resolution data, such as IVMP, will show more variation and detail than coarser resolution data. Engler et al. (2004) found that models using higher resolution habitat predictors performed better than models

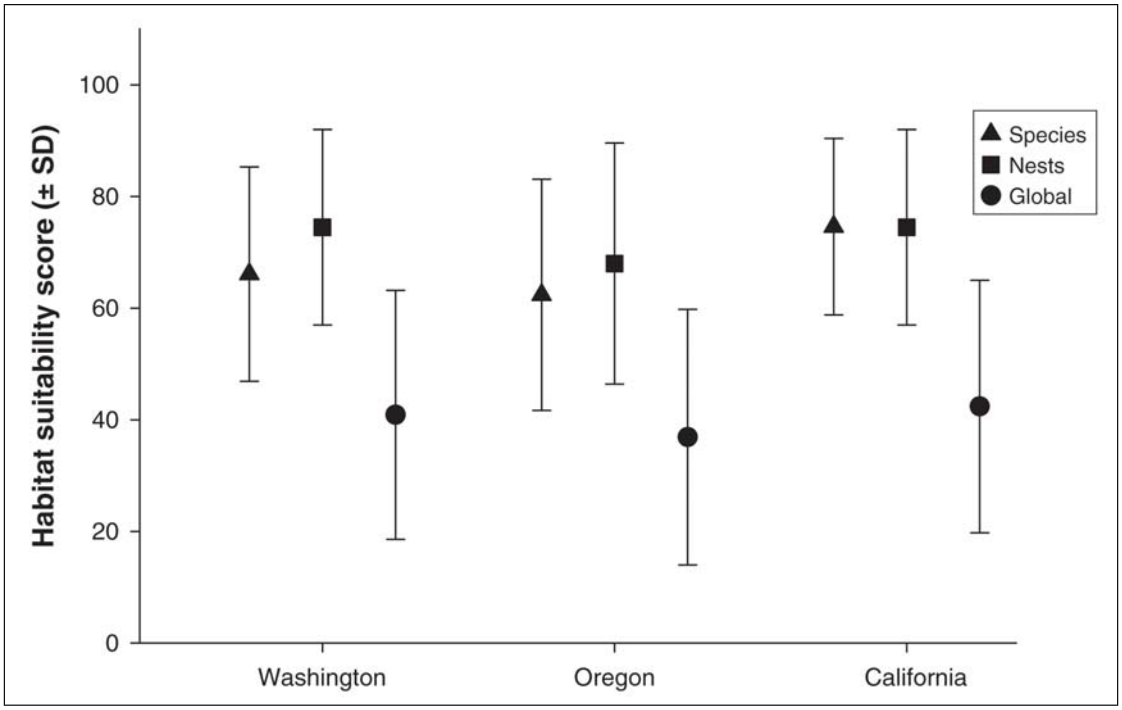


Figure 5-13—Mean habitat-suitability scores computed from the set of occupied polygons (“Species,” n = 111), known marbled murrelet nests (“Nests,” n = 79) and across all lands in each state (“Global”).

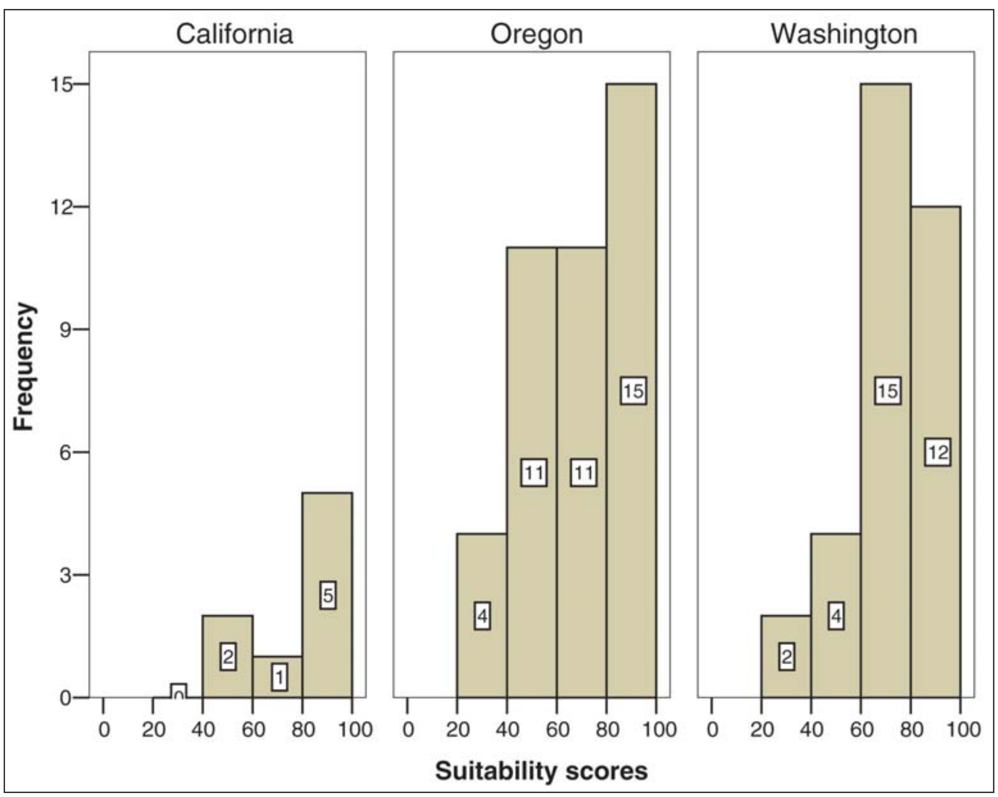


Figure 5-14—Frequency distribution of habitat-suitability scores at known marbled murrelet nest sites by state.

using coarser resolution data (82-ft versus 1,640-ft resolution raster data). The lower model performances they observed at the 1,640-ft resolution (roughly 62-acre pixels) were probably caused by a loss of information that is inevitable when aggregating environmental maps. This aggregation may, in some cases, hide important combinations of habitat predictors that would be expressed with finer resolution data. Similar logic might also apply to the resolution of habitat predictor attribute values. When pixels are assigned a continuous value there is a finer resolution of measure than when coarser, class attributes (e.g., 0 to 4.9 in, 5 to 9.9 in, etc.) are used.

Murrelet Locations

We recognize two primary sources of uncertainty in our marbled murrelet database. First, we assume there are no false positives; that is, we assume murrelets were correctly identified and that their behavior was correctly observed so that sites with occupied detections were not recorded in error. Occupied detections are those that are believed to be associated with nesting (Evans Mack et al. 2003), but it is not clear whether murrelets were actually nesting at all such detection sites. To the extent that occupying behaviors are observed at unsuitable sites, our models could give undue weight to attributes at sites that were not actually used. Conversely, there is evidence that observers fail to detect occupancy when there are, in fact, murrelets in the stand (Cooper and Blaha 2002, Stauffer et al. 2004). Second, there is variation in forest attributes within the polygons that we delineated around murrelet locations. Some pixels that we analyzed as species locations may not have been used by the birds and may not have contributed to site selection by the birds. To the extent that some polygons may have included unsuitable habitat, our description of mean vegetation conditions at the site may have greater variance than a more homogenous polygon of truly suitable habitat.

The allocation of survey effort was not random with respect to vegetation and physiographic variables. Murrelet surveys were not conducted according to any planned survey design. Rather, some of the surveys in our database were done in advance of timber sales in forest stands that were judged likely to be murrelet habitat. As a result, there are possible biases in the distribution of survey effort and hence in the distribution of occupied sites. Some of these biases could include preferential selection of harvest-aged stands, selection of accessible sites, avoidance of very steep areas, and selection of larger stands.

All of these sources of error are propagated through the modeling process. We are not able to put confidence intervals around our estimates; we simply realize that error in vegetation mapping, error in murrelet locations, and biases in murrelet sampling effort all lead to uncertainty in our estimates of potential nesting habitat. We believe that our mapping does give a reasonable estimate of the relative amount of potential nesting habitat within large land areas such as within LUAs at the province scale. We are not confident that any particular pixel is correctly classified or that habitat at a particular project area will be correctly classified, and therefore the maps that we developed are not likely to be useful for fine-scale project planning.

Model Comparisons

We have presented several alternative estimates of the amount and distribution of baseline murrelet nesting habitat, each derived from a different model or set of assumptions. Each has limitations and advantages. Both methods rely on classified satellite imagery and thus both methods are limited by the accuracy of those classifications.

Expert Judgment Model

The primary limitation of this approach is that it relies solely on the knowledge, expertise, and judgment of the team making the suitability classification. A different team might make a different breakdown of HS in relation to older forest classes. We think our assignments were reasonable, but opinions will differ among experts. Our assignments were done without reference to specific data on the occurrence of marbled murrelets, although our review team was well aware of the specific stand conditions at many of the known murrelet locations. We drew on collective knowledge about the basic biology of the species and its habitat requirements to make our classification. The model is very simplistic, perhaps overly so. It does not take into account physiographic variables such as distance to coastline or slope that might influence habitat quality, nor does it consider habitat patch size or other landscape features. We feel, based on past surveys and analyses, that the amount of higher suitability habitat on the nonfederal lands is overestimated in some provinces, particularly the Coast Range of California. In that province, maturing second growth in Mendocino, Sonoma, and Humboldt Counties is assigned as class 4 habitat, but, although the trees are large, they have very few nest platforms and no detections. The large-diameter Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) stands near Cape Mendocino and the King Range are on dry, windy slopes where there is no redwood (*Sequoia sempervirens* [D. Don] Endl.) and researchers have found no detections in these areas (Meyer 2005[6]). Clearly, work is needed to validate our habitat predictions.

This approach has several advantages. First, it can be easily extended to any part of the murrelet's range where older forest information is available. The model is not limited by the availability of murrelet occurrence data. Second, the model is totally transparent. Anyone can see how the suitability classes were derived. The ENFA models, in contrast, compute suitability scores in a less-than-transparent manner; i.e., although factor coefficients are available, one cannot easily compute suitability scores from these coefficients (Hirzel et al. 2002). Third, the expert judgment method will be easy to repeat for future monitoring. Updated estimates of older forest can be easily translated to updated estimates of potential nesting habitat to evaluate trends.

[6] Meyer, C.B. 2005. Personal communication. Research Associate, Department of Botany, University of Wyoming, Laramie, WY 82071.

ENFA Model

The primary limitations of this approach are its reliance on murrelet occurrence and the difficulty in classifying suitable habitat from suitability scores. Reliance on marbled murrelet occupancy to define suitable habitat has advantages and disadvantages. It is advantageous because the behavior of the birds can inform our ratings for habitat quality. This method is a much more objective technique than the expert judgment approach, which is based on our subjective evaluation of existing data on murrelet habitat associations. Murrelet data are disadvantageous in the limitations of these data, as described above. In addition, it is unlikely that managers will obtain a new sample of murrelet locations during the next planning cycle. To use ENFA for the next monitoring update, one likely would need a new sample of occupied locations that come from the time interval over which habitat is being modeled. If these data are not available, it will be problematic to compute revised models. It is not appropriate to use the current set of murrelet locations with updated habitat, unless one can be reasonably sure there have been no significant changes in the attributes of that habitat over the intervening years (see below for suggested alternatives).

Relation to Murrelet Population Estimates

One way to judge these various models is to examine whether any yield stronger relationships between estimated amounts of nesting habitat and at-sea murrelet population size. Such an analysis was presented as part of the recent marbled murrelet status review (McShane et al. 2004: fig. 4.1-2) and showed correlation between total murrelet populations and total suitable habitat at the scale of the six marbled murrelet conservation zones (USFWS 1997; also see Miller et al., chapter 3, and Huff et al. chapter 1, this volume). We repeated this analysis by using our various estimates of suitable habitat (prior to disturbance) and estimates of murrelet population size from strata within conservation zones (Miller et al., chapter 3, this volume). To estimate mean population, we computed the average of the point estimates of murrelet population size in each stratum over the years 2000 through 2003. In the case of conservation zone 1 (Puget Sound) we could not separate the strata and so we used population and habitat estimates for the entire zone. We found strong associations, especially for the ENFA model ($R^2 = 0.88$ for the HS >60 model and $R^2 = 0.86$ for the HS >80 model, fig. 5-15). Our associations did not appear as strong when using the Expert Judgment model ($R^2 = 0.65$) owing to strata 4.1 and 4.2 having a lower than predicted population in relation to habitat and stratum 1.0 having a much greater population relative to habitat (fig. 5-15). Under the ENFA HS >60 model, the regression between mean population and acres of habitat indicates an average of 186 acres per murrelet across all strata.

Comparison of our results with earlier analysis of radar data strengthen our belief that the ENFA HS >60 model yields a reasonable estimate of potential murrelet nesting habitat. Raphael et al. (2002) used radar to count numbers of murrelets flying into each of 10 large drainages on the Olympic Peninsula. These counts were linearly related to amounts of nesting habitat in these drainages and a linear regression of murrelet counts on amount of habitat yielded an estimated average of 396 acres of nesting habitat per murrelet from the HS >60 model and 45 acres per murrelet from the HS >80 model. Not all murrelets on the sea fly inland (e.g., nonbreeders and mates of incubating birds stay on the water), so radar counts should be smaller than the total offshore population of birds. Peery et al. (2004) documented rates of inland flight for breeders and nonbreeders. Based on their data, we estimate an expected ratio of 2.6 birds at sea per bird flying inland. For the HS >60 model, the ratio we observed between acres of habitat per bird from at-sea counts to radar counts is 396/186 = 2.1, a value reasonably close to Peery et al.'s ratio. These results give us added confidence that the ENFA model provides a good estimate of potential nesting habitat for the murrelet.

Future Modeling Considerations

Given the pros and cons of the approaches we used, we conclude that neither the Expert Judgment nor ENFA models are ideal. Given the anticipated difficulty in repeating the ENFA model in future monitoring updates, we believe some version of the Expert Judgment model will have the greatest long-term utility. It should be possible to use ENFA to help build a stronger expert model that would take into account more information (such as physiographic position) and that could be driven from underlying attributes (such as QMD and canopy cover) rather than older forest classes. Improvements would likely result from development of an improved Expert Judgment model for use in the next round of monitoring under the Plan. For the next round, a more consistent approach to vegetation classification across California, Oregon, and Washington would likely lead to stronger models. CALVEG and IVMP differ in several respects (polygon versus pixels, grouped versus continuous attributes) and these differences hamper effective consolidation of data over all physiographic provinces and states. Finally, our habitat modeling was hindered by the lack of occupied site data from inland Zone 2. Because of this, the ENFA model could not be developed for this zone. Although we developed habitat projections for Zone 2 by using the Expert Judgment model, these projections are dubious considering that no occupied sites were found in this zone from 1994 to 2001. We believe that additional study is needed to evaluate the murrelet's breeding range, especially the status of the bird in Zone 2, so that management of suitable nesting habitat can be done more effectively for this species. Our analyses suggest that much of Zone 2 should be considered outside the breeding range of the marbled murrelet.

The Plan has been in operation for only 10 years. This is not enough time for much habitat recovery to occur, and so it is not possible to fully judge how well the Plan has functioned to restore marbled murrelet habitat. Our modeling has resulted in an improved baseline estimate of the amount of suitable habitat. Our modeling has also documented losses of habitat resulting from stand-replacing harvest and fire. We have not been able to document habitat recovery, so that important facet of the Plan's objectives could not be tested. Once sufficient time has elapsed, we will be better able to evaluate this aspect of the Plan. As we noted above, we do not know how many years

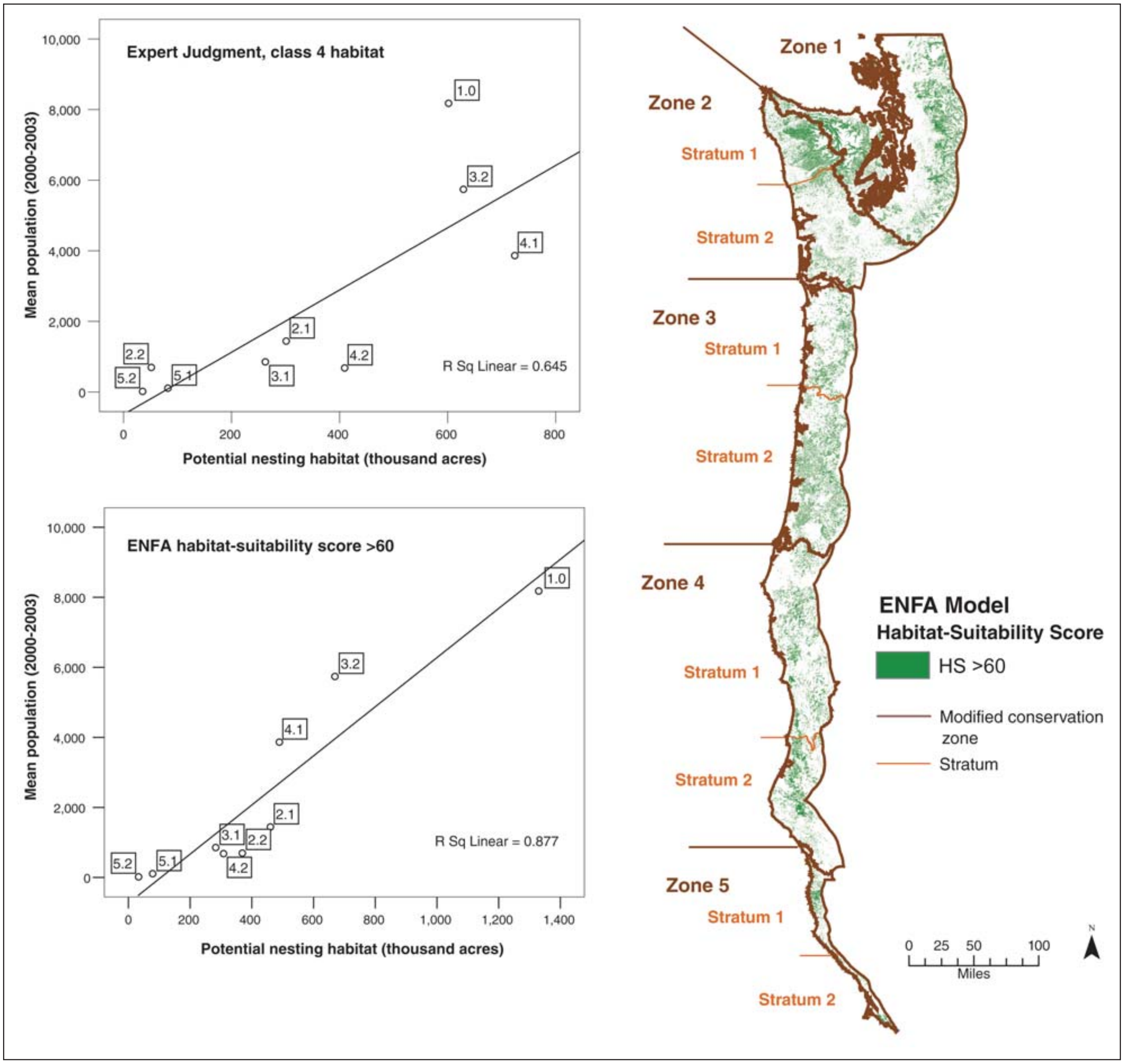


Figure 5-15—Comparisons of estimates of mean murrelet population size with potential baseline murrelet nesting habitat from Expert Judgment model (above) and Ecological Niche Factor Analysis (ENFA) model (below) for all lands in marbled murrelet Zone 1 by modified conservation Zones 1 through 5 and by strata within Zones (e.g., 2.1 denotes conservation Zone 2, stratum 1). The delineation of zones and strata are illustrated in the map (which depicts habitat with Habitat Suitability [HS] >60 from the ENFA model). See Miller et al. chapter 3, this volume, for a description of methods used to estimate murrelet population size. For conservation Zone 1, populations could not be separated among strata, so the entire zone is plotted as 1.0.

might be required for a given stand type to acquire the features making it suitable for marbled murrelet nesting habitat. We are also lacking data on the rate at which newly restored habitat might be colonized by murrelets. Surely this rate will be dependent on the distance of this new habitat from occupied habitat; restored stands adjacent to occupied stands will likely be colonized much more quickly than restored habitat far from occupied stands. We suspect that restored habitat within LSRs has a good chance of rapid recolonization because so much occupied habitat is already present nearby. But this hypothesis deserves testing. Continued murrelet survey work would aid in such an evaluation. Continued surveys will certainly also be important if our HS modeling is to be repeated.

Acknowledgments

This work would not have been possible without the assistance of many people who contributed to the murrelet database and who developed the CALVEG and IVMP vegetation data sets. We are particularly indebted to Diane Evans Mack who helped guide some of the original planning for this analysis and Randall Wilk who developed the murrelet database for Washington. Tom Bloxton and Rick Jordan helped update some of the murrelet observation databases; Rick Jordan also obtained the solar radiation methods. Ray Davis and Alexandre Hirzel helped guide us through the use of BioMapper. Melinda Moeur, Roberto Morganti, and members of the older forest monitoring group provided IVMP data; Ralph Warbington and Brian Schwind provided CALVEG data. Murrelet nest locations in Washington were provided by John Pierce, Bill Ritchie, Peter Harrison, and Tom Bloxton. Nest locations in Oregon and Calfornia were provided by Kim Nelson and Esther Burkett, respectively. Katherine Kimball helped prepare many of the tables. This paper benefited from comments by Diane Evans Mack, Scott Horton, John Pierce, and three anonymous reviewers. Our work was funded by the Pacific Northwest Research Station.

Metric Equivalents

When you know:	Multiply by:	To find:
Inches (in)	2.54	Centimeters (cm)
Feet (ft)	.3048	Meters (m)
Miles (mi)	1.609	Kilometers (km)
Acres (ac)	.405	Hectares (ha)

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Chapter 6: What we have learned

Mark H. Huff, Martin G. Raphael, Sherri L. Miller, S. Kim Nelson, and Jim Baldwin

The marbled murrelet (*Brachyramphus marmoratus*) was federally listed in 1992 as threatened in Washington, Oregon, and California. The Northwest Forest Plan (the Plan), which overlaps the murrelet's range in these three states identifies specific objectives and standards and guidelines to provide for persistence of this species. Because a conservation objective of the Plan was to support stable and well-distributed populations of marbled murrelets, this species is a key indicator of the Plan's potential success. The effectiveness monitoring approach for the marbled murrelet under the Plan has two facets: population and habitat monitoring. The approach recommends assessing population trends at sea by using a unified sampling design and standardized survey methods. For the habitat monitoring, the approach recommends establishing a credible baseline of nesting-habitat data by modeling habitat relations, and then using the baseline to track habitat changes over time. The Plan identified one primary monitoring objective: to determine the status and trends of marbled murrelet populations and nesting habitat in the Plan area.

The chapters in this volume summarize information on marbled murrelet ecology and present the monitoring results for marbled murrelets over the first 10 years of the Plan, 1994 to 2003. The first two chapters provided context and background information to support subsequent chapters: chapter 3 presents population status and trend results from 2000 to 2003 and chapters 4 and 5 present nesting habitat status and trends determined by using different modeling approaches.

In chapter 2, we summarized the literature on the natural history, behavior, habitat associations and population status and trends of the marbled murrelet. Marbled murrelets are noncolonial, secretive alcids that occur along the Pacific Coast of North America. They are generally nonmigratory and remain near nesting areas year round, especially in the southern portion of their range. Murrelets primarily nest in trees in coastal older aged coniferous forests within 52 miles of the ocean. Their breeding season lasts up to 182 days (between April and September) and is highly asynchronous. They do not build a nest, but lay their single egg on platforms created by large or deformed tree branches. Key components of their nesting habitat at the tree and stand scales included large platforms or tree limbs with substrate (generally moss) and cover, high densities of large trees, canopy layering, and naturally occurring canopy gaps to allow access to nest sites. At the landscape scale, murrelet nesting and occupied detections have generally been associated with unfragmented watersheds, large patch size, and minimal edge. Few associations with respect to topographic features, such as elevation, slope, aspect, and distance to marine waters, have been found. Rough estimates of the total current population based on at-sea surveys are as high 950,000 birds throughout the murrelet's range. Major population declines over a decade or more have been reported.

In chapter 3, we reported the first Plan-wide population estimates for the marbled murrelet by using consistent and standard statistical survey methods, which were developed and implemented through the Plan's effectiveness monitoring program. To estimate marbled murrelet population size, we sampled from boats along line transects within 8 km (5 mi) of the Washington, Oregon, and northern California coastline, covering about 8,800 km^2 (3,400 mi^2). From 2000 to 2003, we estimated that the population size of marbled murrelets at sea is about 22,000 birds (on any single day) for the coastal waters adjacent to the Plan. The 95 percent confidence interval for the population size ranges from about 18,500 to 29,000 birds. Four years of surveying marbled murrelets was an insufficient sample to evaluate if marbled murrelet populations changed significantly. We estimated that 6 years of at-sea surveys are needed to detect a 10 percent annual population decline in the coastal water adjacent to the Plan with 95 percent confidence, and 9 years for a 5 percent and 15 years for a 2 percent change. The largest population estimate was in Puget Sound and Strait of Juan de Fuca of Washington; the highest densities were along the coast of Oregon and California, north of the Humboldt-Mendocino County line, and the smallest population and lowest density were from the Humboldt-Mendocino County line south about 200 mi to just south of San Francisco Bay, California.

In chapter 4, we reported use of the survey location data to develop logistic regression equations to predict nesting sites that had habitat attributes similar to those of occupied sites. Then, we used these equations to predict the baseline amount of nesting habitat by using habitat data from a systematic inventory grid that covers federal land in the Plan area. We consider this approach experimental in our quest to develop new methods to monitor long-term habitat change that are repeatable, effective, and cost efficient.

Our logistic regression model predicted that murrelet nesting habitat is more likely at sites that are closer to the sea, are on relatively flat terrain, are topographically cooler, have relatively fewer conifers above pole size (≥10 in d.b.h.), have greater basal area of trees above pole size, and that have greater basal area of larger-diameter trees (>30 in d.b.h.). Overall, our models predicted that most of the area on U.S. Forest and Bureau of Land Management Lands in the Plan area has low odds ratios of suitable nesting habitat for marbled murrelets relative to that of known nesting habitat. Habitat with the higher odds ratios (higher suitability for nesting) was highest in Washington (among three states), and highest in the Oregon Coast Range and Olympic Peninsula among physiographic provinces. Although most of the habitat area with higher suitability was in a reserve land allocation, most reserved land had low odds ratios of being suitable for nesting relative to known nesting habitat. Our models indicate that only about 13 percent of U.S. Forest Service and Bureau of Land Management land are above moderate-quality habitat for nesting. To shift this study from experimental to broader applications, our primary recommendation is to substantially increase the number of murrelet survey sites available to make predictions.

In chapter 5, we reported estimates of the amount and distribution of marbled murrelet nesting habitat determined by using interpreted satellite imagery. We used two spatial modeling approaches: Expert Judgment and Ecological Niche Factor Analysis (EFNA). With the expert judgment approach, we reclassified 22 previously established late-successional and old-growth forest (older forest) classes into 4 classes of murrelet nesting habitat suitability and mapped them. With the ENFA approach we computed habitat suitability scores from vegetation and physiographic attributes based on comparisons of conditions at 111 sites that were occupied by marbled murrelets with average conditions over the physiographic provinces in which the murrelets occurred. Our estimates of amount of potential nesting habitat at the province scale differed from those previously described in the Plan: our estimates were higher in Washington Western Cascades, Oregon Coast Range, and California Coast Range and lower in Olympic Peninsula, Oregon Klamath, and California Klamath. Estimates of amounts of baseline habitat varied with the model used, but all models showed that over 80 percent of baseline habitat on federally administered lands occurred in reserved lands. In reserved lands including national parks, Washington had the highest amount of higher quality habitat, 44 percent of the total; Oregon and California had 36 and 20 percent, respectively, from the Expert Judgment model. Likewise, using the ENFA the totals were 55 percent, 36 percent, and 9 percent, respectively. The Olympic Peninsula province accounted for nearly a quarter of the high-quality habitat on federally administered lands; this habitat was primarily in national parks. Across all lands in the Plan area, we estimated that about 50 percent of higher quality potential nesting habitat occurred on nonfederal lands. Of the two marbled murrelet Inland Management Zones in the Plan, the zone farthest from the coast, Zone 2, accounted for <2 percent of the estimated high-quality habitat on federally administered lands. Potential nesting habitat was lost to fire and harvest in the first 10 years of the Plan; the rate of habitat loss was higher on nonfederal lands. Ingrowth of large-diameter stands has also occurred, and rates of ingrowth appear to exceed rates of loss of such stands, but we are uncertain how much of this ingrowth can be considered nesting habitat.

Metric Equivalents

When you know:	Multiply by:	To get:
Inches (in)	2.54	Centimeters
Miles (mi)	1.609	Kilometers
Square miles (mi^2)	2.59	Square kilometers

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