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THE FIRST 25 YEARS (1994–2018)

Status and Trend of Nesting Habitat for the Marbled Murrelet Under the Northwest Forest Plan, 1993 to 2017

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Cover photo: Spotted owl and marbled murrelet habitat, Oregon coastal forest. Photo by R. Lowe, U.S. Fish and Wildlife Service.

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Abstract

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The objectives of the effectiveness monitoring plan for the marbled murrelet (*Brachyramphus marmoratus*) include mapping nesting habitat at the start of the Northwest Forest Plan (NWFP) and estimating changes in that habitat every 5 years. Using Maxent species distribution models, we modeled the amount and distribution of probable nesting habitat in the murrelet's range in the NWFP area in 1993, 1 year prior to the start of the NWFP, and 25 years later (2017). Within the higher probability nesting habitat, we then estimated the amount of contiguous habitat (core) versus the amount of habitat bounding core habitat (edge) and habitat scattered in small forest fragments (scatter). We considered this "core habitat" as the best habitat. Our models indicate that there were 1.51 million acre of higher probability nesting habitat over all lands in the murrelet's range in Washington, Oregon, and California 1 year prior to the start of the NWFP in 1993. Of this, 0.14 million acre were identified as core habitat, which we defined as intact patches of higher probability nesting habitat >5.56 acre in size. In core habitat, we expected nest predation to be relatively low and the microclimate most favorable for murrelets. Most (68 percent, or 1.04 million acre) higher probability nesting habitat in 1993 was on federally administered lands, with 0.97 million acre (66 percent) in reserved land use allocations. We estimated that nonfederal lands contained 29 percent of all higher probability nesting habitat, but only 13 percent of all core habitat. Thus, the bulk of core habitat was on federal lands. We estimated a net loss of about 1.4 percent in higher probability nesting habitat across the NWFP area and 1.8 percent in core habitat from 1993 to 2017. Timber harvest and wildfire were the major causes of habitat loss on federal lands since the NWFP was implemented. Timber harvest was the primary cause of loss on state and other nonfederal lands, accounting for 99 percent of all attributable losses since 1993. The NWFP has been successful in conserving higher probability nesting habitat on federal lands across the NWFP area, but has been less successful in conserving core habitat. We anticipate that losses of habitat on federal lands will continue because of fires and timber harvest. As forests mature, some of these losses may be exceeded by recovery of currently unsuitable habitat within reserves. However, climate change offers a very real threat, and thus many gains may not be realized as the climate in the NWFP area becomes warmer, drier, and less favorable for developing forest conditions necessary for nesting murrelets. In addition, because losses of nesting habitat continue on private lands, incentives are needed to curb losses to better meet conservation objectives.

Keywords: *Brachyramphus marmoratus*, edge effects, effectiveness monitoring, habitat fragmentation, marbled murrelet nesting habitat, Northwest Forest Plan, old-growth forest.

Contents

Introduction

The marbled murrelet *(Brachyramphus marmoratus)* (hereafter, "murrelet") is a seabird that forages in nearshore marine waters along the Pacific Coast from Alaska south to California and nests inland, commonly in older coniferous forests. The marbled murrelet was selected for monitoring the effectiveness of the Northwest Forest Plan (NWFP) in conserving old-forest species because it was listed as threatened in 1992 under the federal Endangered Species Act, and it is dependent upon late-successional and old-growth forests for nesting (USDI FWS 1992). Murrelets nest mostly on large branches or other platforms in large trees in the NWFP area (Nelson 1997, Ralph et al. 1995). Conservation of the murrelet's nesting habitat is central to the species' recovery in Washington, Oregon, and California (USDI FWS 1997). Because of timber harvest and urban development, only a small percentage (estimated at 5 to 20 percent) of original old-growth forests remain in these three states (Morrison 1988; Norheim 1996, 1997; USDI FWS 1997). Most old-growth forests are in small, fragmented patches or in parks and reserves.

Marbled murrelet effectiveness monitoring (Madsen et al. 1999) assesses status and trends in murrelet nesting habitat and populations to determine whether the NWFP is succeeding in maintaining and restoring nesting habitat. It also monitors if murrelet populations associated with the NWFP are stable, increasing, or decreasing. To address these questions, NWFP murrelet monitoring has two components: habitat and population (Madsen et al. 1999). For habitat monitoring, our approach is to establish a baseline level of nesting habitat in 1993, a year prior to the start of the NWFP, and measure losses and gains to murrelet habitat every 5 years. For population monitoring, population size and trends are monitored at sea using a unified sampling design and standardized transect-based survey methods (Falxa and Raphael 2016; McIver et al. 2021; Miller et al. 2006, 2012; Raphael et al. 2007). Thus, trends in both murrelet nesting habitat and populations are tracked over time. The ultimate goal is to relate nesting habitat conditions to population trends (Madsen et al. 1999). A specific conservation goal of the NWFP is to stabilize and increase murrelet populations by maintaining and increasing nesting habitat (Madsen et al. 1999). Previous monitoring reports by Huff et al. (2006) and Raphael et al. (2011, 2016) assessed the effectiveness of the NWFP in maintaining murrelet habitat in the first 10, 15, and 20 years. The objective of this report is to evaluate the effectiveness of the NWFP in maintaining murrelet nesting habitat in the first 25 years. To that end, in this report, we present new baseline estimates of nesting habitat for 1993, and we compare habitat conditions in 1993 to those in 2017.

Previous NWFP monitoring reports for murrelets (Huff et al. 2006; Raphael et al. 2011, 2016) modeled habitat using species distribution models. We use a similar approach in this report. For model inputs, we used murrelet nest locations and spatial data on forest attributes at the start (1993) and end (2017) of the period from gradient nearest neighbor (GNN) methods. GNN is described more fully below, but it involves using vegetation measurements from field plots, mapped environmental data, and Landsat imagery to ascribe detailed ground attributes of vegetation to each pixel in a digital landscape map, along with accuracy assessments of those attributes (Ohmann and Gregory 2002; Ohmann et al. 2010, 2014). The GNN data used in this report represent an update to the GNN models used in previous monitoring reports. We also used updated forest disturbance data produced by the U.S. Department of Agriculture (USDA), Forest Service's Laboratory for Applications of Remote Sensing in Ecology using ensemble LandTrendr methodology (Cohen et al. 2018). These maps are part of a larger national dataset produced by the Forest Service's Landscape Change Monitoring System (LCMS), updating and replacing the maps used in the NWFP 20-year monitoring report (Raphael et al. 2016). We used LCMS maps to attribute a cause of habitat loss for nesting habitat that was lost between 1993 and 2017. Another change from previous reports (e.g., Raphael et al. 2016) is that we used only murrelet nest sites for training our model. In this report, we did not include "occupied sites" in this report (stands with observations of murrelet behaviors indicative of nesting; see below for more information). This report also differs from previous reports in our definitions of core habitat from landscape habitat pattern analyses. Core habitat represents unfragmented patches of nesting habitat in forest interiors and provides better quality habitat compared to forest edges and small, scattered patches. In the 20-year report, Raphael et al. (2016) used a 295-ft (90-m) edge width to differentiate between core and edge habitat. After reviewing the literature, we found greater support for using a 197-ft (60-m) edge width in this report.

All of these items are described more fully in the methods below. Overall, the baseline (1993) estimates of habitat in this report establish new baseline estimates of habitat over the 20-year estimates in Raphael et al. (2016). We then compared these baseline estimates to estimates of habitat in 2017 to assess changes in murrelet nesting habitat since the start of the NWFP.

Methods

Study Area

Our analysis area (the NWFP area) for modeling nesting habitat was all habitat-capable land within the range of the murrelet in Washington, Oregon, and California, with a few exceptions. We did not model habitat in the NWFP inland zone 2 (fig. 1) (inland zones are described below) in Oregon and California. We also did not model habitat south of San Francisco because those areas are outside the NWFP area.

Habitat-capable lands were defined as lands capable of supporting forest and comprised approximately 20 million acre combined (table 1). They were delineated for all of our map-based analyses by a 98-ft (30-m) resolution raster map that represented areas within the NWFP boundary. This map was created for the 15-year monitoring reports (Davis et al. 2011, Raphael et al. 2011) and was not updated for this report. It was largely based on the U.S. Geological Survey (USGS) Gap Analysis Project and the "impervious layer" from the National Land Cover Database (Herold et al. 2003: Vogelmann et al. 2001). Lands that are not habitat-capable include urbanized areas, major roads, large agricultural areas, water, lands above tree line, snow, rock, and other nonforested features. We used this map to exclude (or mask)

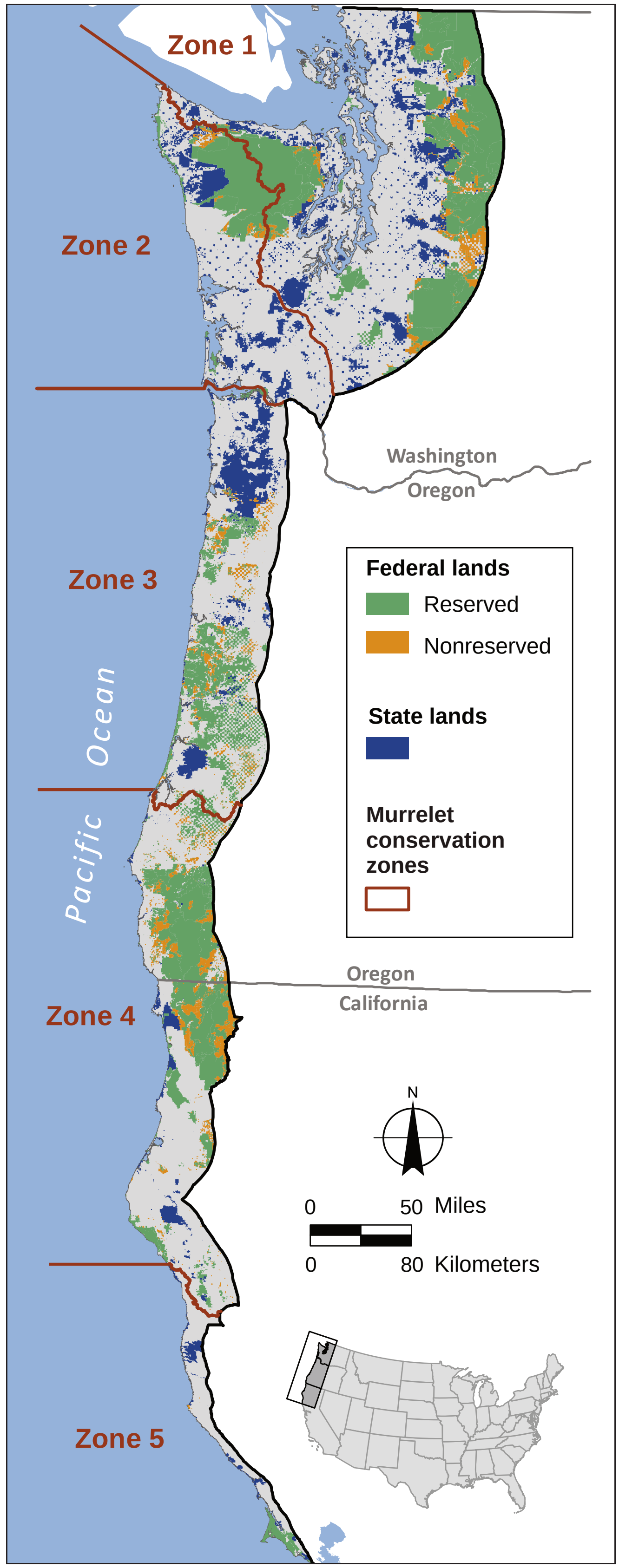

Figure 1—Northwest Forest Plan reserved and nonreserved land use allocations on federal lands within the range of the marbled murrelet. Also depicted are state lands and locations of murrelet conservation zones. Refer to the text for a description of murrelet inland zones and a discussion of the area that was mapped in this report. Nonfederal and nonstate lands are shown in gray.

Table 1—Acreage of habitat-capable lands in the Northwest Forest Plan (NWFP) area used to model nesting habitat for murrelets in this report

	Federal reserve		Federal nonreserve		State		Other landowner		Total
	Acres	% of area	Acres	% of area	Acres	% of area	Acres	% of area	Acres
State									
Washington	3,053,774	28%	446,219	4%	1,646,923	15%	5,702,398	53%	10,849,314
Oregon	1,990,458	30%	458,740	7%	694,985	11%	3,465,316	52%	6,609,499
California	783,449	24%	217,955	7%	192,550	6%	2,056,088	63%	3,250,042
Conservation Zone									
CZ 1	2,391,094	32%	376,491	5%	1,123,342	15%	3,600,604	48%	7,491,531
CZ 2	662,679	20%	69,728	2%	523,581	16%	2,101,794	63%	3,357,782
CZ 3	998,467	22%	240,424	5%	685,425	15%	2,632,507	58%	4,556,823
CZ 4	1,747,921	37%	435,988	9%	138,647	3%	2,438,735	51%	4,761,291
CZ 5	27,519	5%	282	0%	63,463	12%	450,161	83%	541,425
NWFP area total	5,827,681	28%	1,122,914	5%	2,534,458	12%	11,223,802	54%	20,708,855

Note: Habitat-capable lands are defined as areas capable of growing forest; they exclude urban areas, major roads, water, land above tree line, agricultural areas, and other nonforested features.

all but the habitat-capable areas for each time period map. Therefore, estimates of habitat area and other analyses in this report were only applied to habitat-capable areas. Importantly, the term “habitat capable” is not synonymous with the terms “nesting habitat” or “higher probability nesting habitat.” We estimated that only a small percentage of habitat-capable lands are suitable for murrelet nesting, as described in our results.

Murrelet Inland Zones—

Murrelet inland zones were established in 1993 to reflect the fact that most murrelet nests have been found near the coast (FEMAT 1993) (fig. 2). Inland zone 1 extends from the coastline to 40 miles inland in Washington and 35 miles in Oregon. It is more variable in California being 25 miles wide at the northern end and narrower toward the southern end of the NWFP area, tracking the narrower distribution of potential forested habitat in that area. In our mapping of murrelet habitat for this report, we included NWFP inland zone 2 in Washington, which extends 55 miles inland, because nests have been found in zone 2 in Washington. Our habitat modeling excluded NWFP inland zone 2 in Oregon and California because murrelet nests have not been found in those areas, and survey-based studies did not find murrelet use of inland zone 2 in southern Oregon (Alegria et al. 2002) or northern California (Hunter et al. 1998). It is worth noting that few nest searches or surveys have been conducted in inland zone 2 in Oregon north of the Siskyou Mountains. Murrelet presence and occupancy has been confirmed in some areas within this zone (USDI BLM, n.d.).

Murrelet Conservation Zones—

Similar to previous reports (Raphael et al. 2011, 2016), we estimated murrelet nesting habitat for each murrelet conservation zone (figs. 1 and 2). Conservation zones were established in the murrelet recovery plan (USDI FWS 1997) and divided the murrelet’s range south of Canada into six zones. Only conservation zones 1 through 5 are within the NWFP area and included in this report. The inland divisions of these conservation zones were determined by the murrelet monitoring team to associate terrestrial nesting habitat with marine areas as described in the recovery plan. For this report, we used a revised inland boundary between conservation zones 1 and 2 to more appropriately reflect this association.

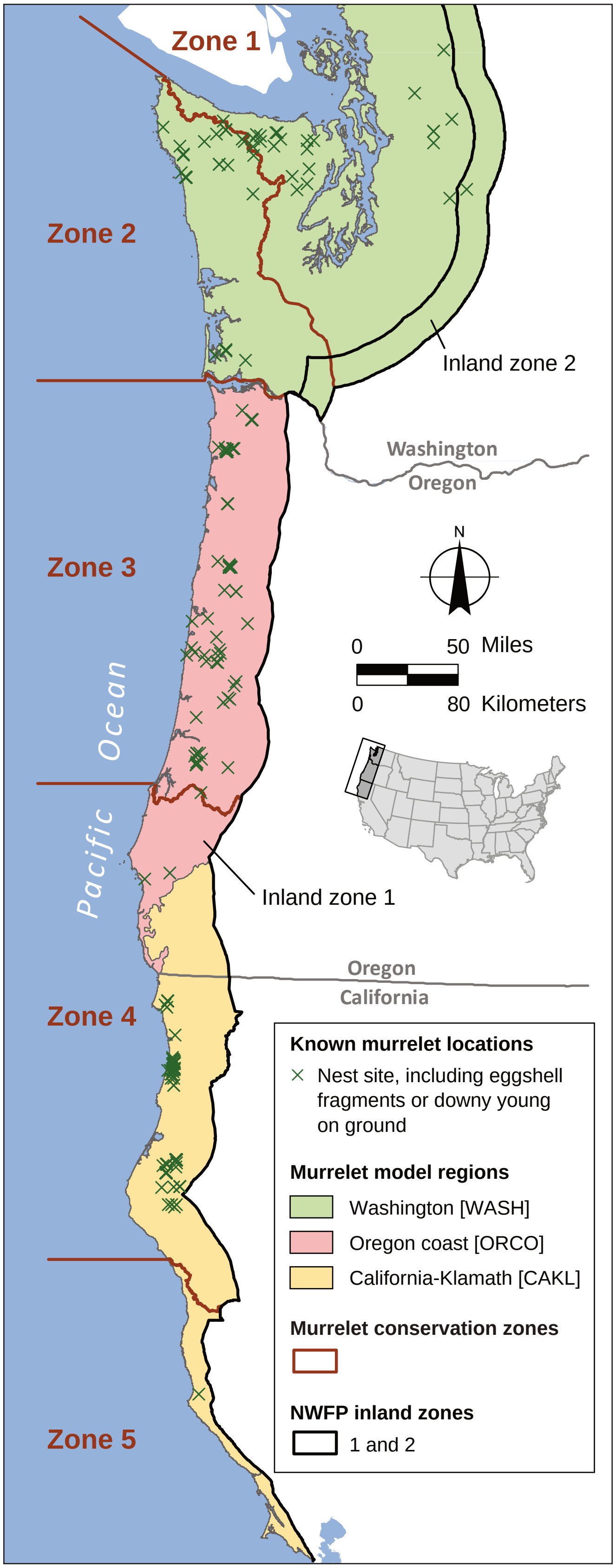

Figure 2—Locations of known marbled murrelet nest sites (including downy young and eggshells) used for training our nesting habitat model in this report and the three model regions used in our analysis. Also depicted are murrelet conservation zones and inland zones.

Land Ownership and Land Use Allocations—
We provide estimates of murrelet nesting habitat for state, federal, and "other" lands. Our other land category included all nonstate and nonfederal lands, such as private, tribal, county, and municipal lands. For federal lands, we summarized amounts of habitat separately for reserve and nonreserved land use allocations. The designation of all federal lands into reserved and nonreserved land use allocations was done during the implementation of the NWFP. These land use allocations are managed differently (Huff et al. 2006). On reserved lands, commercial timber harvest is generally not permitted and younger stands, if managed, are managed to attain tree size and stand structure resembling old-growth in the long term (Thomas et al. 2006). Reserved lands include national park lands and designated wilderness areas, as well as national forest and Bureau of Land Management lands designated as late-successional reserves. Nonreserved lands are all other federal lands on which, in many cases, commercial timber harvest is permitted.

Updates to the original 1994 land use allocation GIS map were produced in 2002, 2009, 2013, and 2017 for the 10-, 15-, 20-, and 25-year monitoring reports, respectively. Each successive update improved the accuracy of some of the mapped allocation boundaries based on work by individual federal entities. Updates also corrected some mapping errors (i.e., "gaps" and "slivers") that had been inadvertently introduced during earlier mapping efforts. More importantly, these updates incorporated major allocation changes that had occurred since the previous mapping effort. Examples of these types of changes include the designation of new wilderness areas and land swaps between federal and nonfederal entities, as well as updates to land and resource management plans.

Each update represented a significant amount of time and effort on the part of monitoring team personnel, who made every effort to procure and incorporate the best available data at that time. The current (2017) version of the land use allocation areas (fig. 1) represents the cumulative result of all previous updates. Even so, some issues and limitations remain. These include the inability to map NWFP riparian reserves (which can cover significant amounts of land where stream densities are high) and inconsistencies in how administratively withdrawn areas (e.g., withdrawn from the acres available for timber harvest at the discretion of individual national forests) were mapped (Davis and Lint 2005, Huff et al. 2006). The lack of mapped NWFP riparian reserves, as Moeur et al. (2005) noted, is due to "…the [NWFP] scale, they cannot be reliably distinguished from [the adjacent nonreserved or matrix lands] because of a lack of consistency in defining intermittent stream corridors and varying definitions for riparian buffers." As those authors note, this affects only NWFP riparian reserves that are not within another NWFP reserve type (such as late-successional reserve). This limitation has no effect on whether a given area was designated as nesting habitat, but would affect whether habitat in a riparian area on federal lands is classified as reserved or nonreserved in our analysis. This resulted in our estimates for reserved federal lands being biased low and estimates for federal nonreserved lands being biased higher by the same amount, than if riparian reserves were mapped. The NWFP initially estimated the amount of riparian reserve within nonreserved land use allocations to represent about 32 percent of the nonreserved land use allocation area of federal lands (Raphael et al. 1994, USDA and USDI 1994a). Our analyses (below) assigned about 6.4 percent of murrelet nesting habitat on NWFP lands to nonreserved land use allocations, for the baseline year. Applying the 32 percent estimate to 6.4 percent suggested that about 2.0 percent of nesting habitat in federal riparian reserves would be incorrectly classified as nonreserved; this provides a rough estimate of the potential error resulting from the lack of mapped riparian reserves. Another minor issue involves a small amount of federal lands that are awaiting official land use allocation designation. These areas, which represent about 0.2 percent of the total area modeled, are identified as "not designated" in the 2017 map and are reported in the nonreserved category in this report.

Land use allocations within the NWFP area will continue to change. The land use allocation land use allocation map will be updated for each successive monitoring effort in the future. Previous versions of the land use allocation map have been archived, and for monitoring purposes, we always report vegetation and habitat changes within the reference frame of the most up-to-date version.

Analytical Methods

To assess the status and trend of nesting habitat for marbled murrelets, we used species distribution models (Guisan and Zimmermann 2000) to model the relative suitability of forests within the NWFP area as murrelet nesting habitat. We used the modeling software Maxent (version 3.4.1, Phillips et al. 2016) similar to methods used for the 15- and 20-year reports (Raphael et al. 2011, 2016).[1] Maxent uses a machine learning process to estimate the most uniform probability of occurrence (maximum entropy) at unobserved (background) locations given known constraints (observations of presence data). It estimates the relative probability of occurrence at unobserved locations throughout the study area by comparing environmental conditions (covariate values) at locations where murrelets nest (presence sites) to conditions at the unobserved locations, assigning a higher probability of occurrence to locations with environmental conditions more similar to presence sites (Baldwin 2009). It uses presence-only data (in our study, known murrelet nesting locations) and does not use locations where the species is known to be absent, as data is very scarce on sites where absence has been reliably documented.

When compared to other habitat modeling approaches, Maxent performs as well or better than many methods (Elith et al. 2006, Hernandez et al. 2006, Phillips et al. 2006, Merow and Silander 2014). The Maxent approach has been criticized (e.g., Royle et al. 2012, Yackulic et al. 2013; see also the response by Phillips and Elith 2013) because some authors find that presence-only models do not perform as well as presence-absence models. However, available data on locations of murrelet absence do not exist, which favored a presence-only model for our purposes. Using a set of murrelet nest locations, Raphael et al. (2011) compared the performance of Maxent with other modeling platforms for predicting nesting habitat suitability and concluded that Maxent performed better. For this report, we conducted a

[1] 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.

simple comparison of several modeling approaches (Maxent, Random Forests, and Maxlike) with 2012 GNN data using the R package SDM (Naimi and Araujo 2016) and found that using these other methods did not markedly improve model performance. We also considered using an expert judgment model similar to Raphael et al. (2006), but in the end we found no compelling reason to adopt another modeling platform for the current analysis.

Data sources

GNN habitat data—

As inputs to our Maxent models, we used habitat data generated by GNN maps of forest composition and structure (Ohmann and Gregory 2002). GNN maps were developed specifically for large-scale analyses of forest conditions as part of the NWFP Effectiveness Monitoring Program (Moeur et al. 2005, 2011; Ohmann and Gregory 2002; Spies et al. 2007). The GNN method integrates vegetation measurements from regional grids of field plots, mapped environmental data, and Landsat imagery to ascribe detailed attributes of vegetation to each pixel in a digital map (Ohmann and Gregory 2002; Ohmann et al. 2010, 2014). GNN mapping also provides a suite of diagnostics detailing model reliability and map accuracy (e.g., Oregon State University's Landscape Ecology, Modeling, Mapping, and Analysis project [https://lemma.forestry.oregonstate.edu/projects/nwfp]).

The GNN vegetation attribute data provided the source of covariates used for our habitat modeling. In the current iteration of GNN modeling, the analysis created annual attribute maps for 1986 through 2017 and covered the entire breadth of murrelet nesting range within the NWFP area. As noted above, we restricted our analyses to the bookend years of 1993 and 2017. We called these two time periods "bookends" because the changes in habitat that we analyzed and report on occurred between these two endpoints. Thus, we used satellite imagery from GNN from 1993 and 2017 in this report. The on-the-ground plot data used by GNN to create all vegetation maps in this report covered the period from 2001 to 2016. The resolution (i.e., pixel size) of the GNN maps was 30 m.

Changes to GNN from previous reports—

For the 15- and 20-year reports, the GNN covariate maps were developed using Landsat time-series data that were temporally normalized using the LandTrendr algorithm (Raphael et al. 2016). The GNN covariate data used for the 25-year report included several improvements over the 20-year data and methods:

1. New imputation method: The 20-year data used a nearest neighbor algorithm with k = 1 in which the covariate value of a pixel to be imputed is that of the field plot with the minimum distance from the pixel in gradient space (Ohmann and Gregory 2002). The 25-year GNN data uses a k = 7 nearest neighbor imputation, using the weighted mean from the first seven nearest neighbor plots. The nearest neighbor is weighted most heavily, and weights decline exponentially from the nearest neighbor (Bell et al. 2015). As a result, on average, 99 percent of the bootstrap values for a given pixel are accounted for, compared to ~63 percent for k = 1 (Bell et al. 2015). Using k = 7 imputation has the advantage of diminishing the effects of some of the more extreme values in nearest neighbors that may influence pixel-based estimates of GNN attributes.
2. Using only annual Forest Inventory and Analysis (FIA) field plots: The 20-year GNN data were built using plot-based data from multiple sources: FIA periodic plots, FIA annual plots, and Current Vegetation Survey (CVS) plots on Forest Service Region 6 and Bureau of Land Management lands (Davis et al. 2015). Each of these sources has a different subplot configuration and sampling protocol for live and standing dead trees (snags) and coarse woody debris. Previously, plots were selected for imputing vegetation characteristics to each pixel that were nearest in time to the GNN year being modeled. In the 20-year GNN, for each pixel and analysis year, any source could have been used to impute vegetation characteristics. Differences in inventory methods between FIA and CVS plots sometimes resulted in differences in the GNN attribute derived from the different plot types. That is, changes in forest attributes modeled from GNN could be due to differences in inventory methods

from using an FIA plot in one year and a CVS plot in another year. Alternatively, changes could be due to actual changes in forest attributes. In the 25-year GNN, a decision was made to include only annual FIA plots to improve model accuracy for the 25-year analysis. The 25-year GNN was also built using 5 additional years of plot measurements, resulting in plot data that spanned from 2001 to 2016.

3. Advances in Internet-based (or "cloud-based") geoprocessing: Advances in cloud-based computing efficiency and the release of Google Earth Engine (Gorelick et al. 2017) streamlined many aspects of the GNN modeling process, resulting in faster processing times (Kennedy et al. 2018). This had many advantages. For example, in the 20-year GNN, it was only practical to model the bookend years of 1993 and 2012. In the 25-year GNN, it was possible to model habitat and GNN attributes for every year from 1986 through 2017. We took advantage of this larger dataset when plotting acres of nesting habitat lost to different disturbance agents over time.
4. Less restrictive stabilization mask: Previous stabilization methods held spectral indices constant across years for all pixels that did not experience disturbance or recovery (see Davis et al. 2015, n.d.), meaning that the primary mode of change was disturbance (e.g., loss of older forest). This may bias results by underrepresenting gains in older forests. In contrast, the cur-

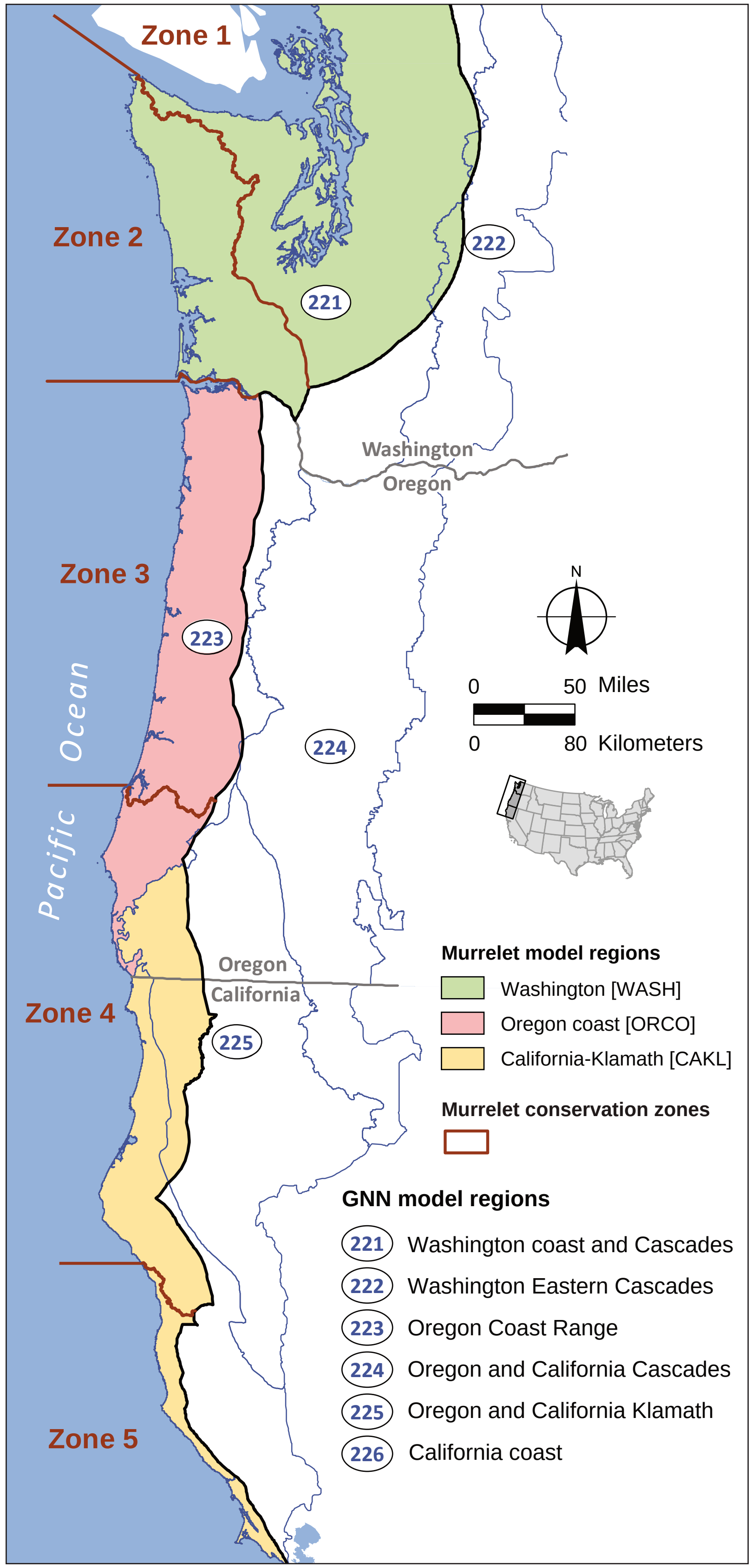

Figure 3—Murrelet model regions used to map nesting habitat in this report (WASH, ORCO, CAKL) as well as GNN model regions developed by the Landscape Ecology, Modeling, Mapping, and Analysis project. for building gradient nearest neighbor vegetation maps.

rent imagery stabilization method minimizes unreasonable modeled changes in older forests, while still allowing for the transition of young stands into mature forest conditions. Whereas the forest area stabilized in the previous NWFP 20-year reports was 15.7 million hectare (43.1 percent of total forest area), stabilization in the current models only accounted for 9.9 million hectare (27.1 percent).

5. Using LandTrendr multispectral ensemble maps of forest disturbance: For the 15- and 20-year reports, the GNN covariate maps were developed using mapped disturbances from a single band LandTrendr algorithm based on normalized burn ratio (NBR) (Ohmann et al. 2014). The 25-year GNN uses a multispectral ensemble model, which reduces error rates, increases the accuracy of the resulting GNN maps, and enables better detection of low-severity disturbances (Cohen et al. 2018). These maps were produced as part of a larger national dataset produced by LCMS. We used LCMS maps to attribute losses of murrelet nesting habitat to different disturbance types.

GNN and murrelet model regions—
In this report, we incorporated two different sets of modeling regions to account for variation in forest composition across the NWFP area. First, the GNN data that overlapped the murrelet's range was developed based on six GNN modeling regions, which in turn were based on physiographic provinces. Most of the murrelet range is covered by four GNN model regions (fig. 3): (1) Washington coast and Cascades, (2) Oregon Coast Range, (3) Oregon and California Klamath, and (4) California coast. For modeling murrelet nesting habitat, the scarcity of murrelet nests (presence locations) from some GNN model regions forced us to combine multiple GNN model regions into one murrelet model region to have sufficient presence locations to train the Maxent models. For example, no murrelet nests have been found in the Klamath region, but many have been found in coastal California; thus, we combined the GNN Oregon and California Klamath model region with the GNN California coast model region into a single murrelet (Maxent) modeling region. Overall, for our analysis, we therefore used three murrelet model regions: (1) Washington (WASH; predominately the GNN Washington coast and Cascades model region), (2) Oregon coast (ORCO; predominately the GNN Oregon Coast Range model region), and (3) California and Klamath regions (CAKL; the GNN Oregon and California Klamath, and California coast model regions). GNN and murrelet model regions are depicted in figure 3.

GNN covariates used for murrelet nesting habitat model—
We started with the 15 possible environmental covariates included in Raphael et al. (2016). These covariates described various aspects of forest structure important for murrelet nest site selection and were initially selected based on a review of the literature and expert opinion. From this list, we selected covariates that met a baseline set of criteria for accuracy to include in our 25-year models (tables 2 and 3). Accuracy assessments for all GNN covariates were determined by comparing observed values from field plots with the GNN-predicted (modeled) values for those same plots and were provided by the GNN modeling team. More information on the GNN map products is available at https://lemma.forestry.oregonstate.edu/data. We included only covariates with a correlation coefficient of at least 0.60 to 0.65 and low root mean square error values. We eliminated covariates that did not meet these baseline levels of accuracy from consideration. Thus, three covariates that were used in Raphael et al. (2016) were eliminated in this report because of accuracy issues in the underlying data: PLATFORMS, TPHC_GE_100, and MOD_OGSI_NWFP. Other covariates had high accuracy assessment in one or two GNN model regions but not in a third. For example, AGE_DOM_NO_REM had relatively high accuracy in GNN model regions 221 and 223 (r = 0.77 and 0.74, respectively), but low accuracy in the GNN model region 226 (r = 0.49) (table 3). Therefore, we included AGE_DOM_NO_REM in models for WASH and ORCO murrelet model regions, but not for CAKL. This approach differs from that of Raphael et al. (2016), in which the same set of covariates were used to model murrelet habitat in all three states. We also excluded the parameter PCTMATURE_50 that was used by Raphael et al. (2016), which estimates the percent-

Table 2—Gradient nearest neighbor (GNN) covariates used as inputs to Maxent for the three model regions assessed in this report

Abbreviation	Description	Units	Model region
AGE_DOM_NO_REM	Basal area-weighted stand age based on field recorded or modeled ages of dominant and codominant trees, excluding remnant trees	Years	WASH, ORCO
CANCOV_CON	Canopy cover of all conifers	Percentage	WASH, ORCO, CAKL
CANCOV_HDW	Canopy cover of all hardwoods	Percentage	CAKL
DDI	Diameter diversity index: measure of structural diversity of a forest stand based on tree densities in different diameter at breast height classes (5-24 cm, 25-49 cm, 50-99 cm, and ≥100 cm). See McComb et al. 2002 for details.	No. of units	WASH, ORCO, CAKL
MNDBHBA_CON	Basal area-weighted mean diameter of all live conifers	Centimeters	WASH, ORCO
MULTISTORY_50	Percentage of 50-hectare circular area classified as GNN CANCOV_LAYERS (number of tree canopy layers present) equal to 3	Percentage	WASH, ORCO, CAKL
PISI_BA_GE_13	Basal area of Sitka spruce (*Picea sitchensis*)	Square meters per hectare	ORCO
QMDC_DOM	Quadratic mean diameter of dominant conifer trees	Centimeters	WASH, ORCO
SESE_BA_GE_13	Basal area of coast redwood (*Sequoia sempervirens*)	Square meters per hectare	CAKL
STNDHGT	Stand height, computed as average of heights of all dominant and codominant trees	Meters	WASH, ORCO, CAKL

Table 3—Accuracy assessment for gradient nearest neighbor (GNN) attributes used to model nesting habitat

	Washington coast and Cascades—221		Oregon Coast Range—223		Oregon and California Klamath—225		California coast—226	
GNN attribute	RMSE	Correlation coefficient	RMSE	Correlation coefficient	RMSE	Correlation coefficient	RMSE	Correlation coefficient
AGE_DOM_NO_REM	0.57	0.77	0.57	0.74	0.55	0.57	0.68	0.49
CANCOV_CON	0.20	0.80	0.28	0.78	0.41	0.75	0.41	0.78
CANCOV_HDW	1.29	0.72	0.79	0.69	0.66	0.72	0.46	0.60
DDI	0.32	0.77	0.34	0.77	0.38	0.69	0.33	0.63
MNDBHBA_CON	0.43	0.70	0.45	0.75	0.53	0.54	0.62	0.49
PISI_BA_GE_13	8.06	0.24	3.89	0.63	30.64	0.04	11.96	0.11
QMDC_DOM	0.43	0.70	0.45	0.77	0.56	0.53	0.64	0.47
SESE_BA_GE_13	NA	NA	13.37	0.09	13.58	0.28	1.65	0.72
STNDHGT	0.34	0.75	0.32	0.83	0.48	0.62	0.41	0.62

Values are normalized root means square error (RMSE) and Pearson correlation coefficients for individual GNN vegetation model regions. This list includes nine attributes used directly as covariates. The derived covariate MULTISTORY_50 is not included. NA indicated that a covariate was not used in modeling nesting habitat in that model region. Column headings indicate the GNN model regions and model region numbers for regions responsible for most of the land area within the murrelet model regions, which are depicted in figure 2. See figure 3 for a map of GNN model regions.

age of area with mature forests around each nest, because the patchiness of habitat around murrelet nest sites was modeled with our morphological spatial pattern analysis (MSPA) (see below).

We further refined our models by including basal area of Sitka spruce (*Picea sitchensis* (Bong.) Carrière) in the ORCO murrelet model region and coast redwood (*Sequoia sempervirens* (Lamb. ex D. Don)) in the CAKL murrelet model region. We included basal area of these tree species to reflect the possible selection of redwood and spruce stands by murrelets in these regions. In this report, we did not consider covariates that were based on abiotic factors (such as FOG, JULY_MAXT, and SMR_PRECIP from Raphael et al. 2016). Our final covariate list is summarized in table 2, along with descriptions of each of the covariates. Accuracy assessments for GNN attributes are provided in table 3.

Murrelet nest site data sources—
We used murrelet nest locations from agency records as presence sites for training Maxent models. For Washington, we used records of 47 nest sites from a database maintained by the Washington Department of Fish and Wildlife. For Oregon, we obtained 71 nest locations from a database currently maintained by Oregon State University and populated with records from the Forest Service, Bureau of Land Management, Oregon Department of Forestry, Oregon Parks and Recreation Department, and Oregon State University (Nelson, n.d.). California sources included 26 nests obtained from a database maintained by the California Department of Fish and Wildlife, supplemented by records assembled by the U.S. Fish and Wildlife Service, and also included a number of nests located by a radiotelemetry study (Hébert and Golightly 2008). Because of small sample sizes, we supplemented these nest locations with records of eggshell fragments (n = 56) and downy young (n = 11) found on the forest floor. We used only records in which inspection of digital aerial photographs confirmed that undisturbed forest was present at the location in 1993, our baseline bookend year. We manually screened the data on known site locations with the aid of aerial photography and communications with original data sources to confirm and correct locations and remove duplicate records.

To provide a more representative sample of environmental conditions used by murrelets for nesting, Raphael et al. (2011, 2016) supplemented all the aforementioned nest sites with an equal number of "occupied sites." Occupied sites are locations where breeding behaviors (i.e., occupied behaviors) have been observed in forest stands (Evans Mack et al. 2003). Surveys for occupied behaviors are commonly used before timber harvests and other forest management activities to assess whether murrelets are using a given stand for breeding. Surveys for occupied sites, rather than nest searches, are used because this species' nests are extremely difficult to locate. In previous reports, Raphael et al. (2011, 2016) included a random subsample of occupied sites as training sites in Maxent models, which increased sample sizes and spatial distribution of training sites. However, there are potential problems associated with using occupied sites, and we did not include occupied sites as training data in this report. First, occupied behaviors rarely provide an exact nest location. Examples of occupied behaviors include murrelets circling at or below the forest canopy; circling above the canopy by no more than 1.0 canopy height; flying through in a straight flight path below the canopy; landing in, perching in, or departing from a tree; or birds emitting ≥ three calls from a fixed point in a tree within 100 m (328 ft) of an observer (Evans Mack et al. 2003). Second, there is error associated with the exact spatial location of many occupied behaviors; behaviors such as circling above or flying through the forest canopy cannot be assigned to a specific pixel. This could create spatial inaccuracies in our species distribution models. In addition, surveys for occupied sites are generally associated with timber sales and thus may be biased to lands subject to harvest. Some areas that are used by murrelets for nesting, such as state parks, national parks, and national forest wilderness areas are under sampled. Finally and perhaps most significantly, we compared means and distributions of covariate values among nest sites, occupied sites, and random sites and found that attributes of occupied sites were more similar to random sites than to nest sites, indicating that forest attributes at occupied sites were not a good representation of nesting habitat, and inclusion of these occupied sites would lead to misleading model results. With these factors in mind, we were concerned that our use of occupied sites as training points would cause bias when modeling nesting habitat, and therefore we used only nest sites as training data in this analysis.

Model Refinements

Once we selected our final set of covariates and training sites, we conducted a series of Maxent model runs to evaluate model performance. To evaluate model performance, we used training and test model gain, and area-under-the-curve (AUCs) statistics (Boyce et al. 2002, Fielding and Bell 1997). Gain is closely related to deviance, a measure of goodness of fit used in generalized additive and generalized linear models and is available as part of the model output in Maxent (Phillips et al. 2006). The lowest value of gain is 0, and gain usually increases toward an asymptote as the fit between the model and the training data improves. During a run, Maxent generates a probability distribution over pixels in the grid, starting from a uniform distribution and repeatedly improving the fit to the data. The gain is defined as the average log probability of the presence samples, minus a constant that makes the uniform distribution have zero gain. At the end of a run, the gain indicates how closely the model is concentrated around the presence samples; for example, if the gain is 2, it means that the average likelihood of the presence samples is $\exp(2) \approx 7.4$ times higher than that of a random background pixel (Phillips, n.d.). For a given model run, separate gain statistics were generated for the training (75 percent) and test (25 percent) portions of the available presence sites.

The other measure of model performance, AUC, is the area under a receiver operator characteristic curve (Boyce et al. 2002, Hirzel et al. 2006). The AUC statistic is a measure of model performance that illustrates how well one can distinguish presence sites from the available background sites (some of which are likely to be occupied by or suitable for murrelets). AUC values range from 0 to 1.0. Location data that cannot be distinguished from the background with any greater probability than random would yield an AUC score of 0.5. We present AUC values generated using test data, which is data held back during model development and then used to test model fit and accuracy. Test AUC values provide a measure of model performance in classifying an independent set of presence points.

Maxent also provides a choice of covariate relationships, or "features" to include in a model: linear, quadratic, threshold, hinge, and product. These features set the possible shapes of the relationship between a covariate and the response (i.e., the Maxent probability distribution) or allow for covariate interactions (product features). A user can select any combination of these feature types. A model with linear features requires the fewest parameters, as only two parameters (slope and intercept) are estimated for each covariate. Quadratic relationships require both slope and intercept as well as exponent parameters for each covariate. The hinge feature creates a piece-wise approximation to any distribution. The number of parameters for any one covariate increases for each "hinge" in the modeled distribution, which can result in a complex distribution and many parameters. The product feature allows for interactions among all pairs of covariates. The total number of parameters for any model depends, therefore, on the types of features selected and the complexity of the response curves between the covariates and the probability scores. With the 25-year data, we used linear and product features to optimize performance because a quadratic relationship was not expected for any of the covariates used in our analysis. This method differs from that of Raphael et al. (2016) in which linear, quadratic, and product features were used.

In addition, Maxent has a "regularization" constant that can be specified. Increasing the regularization value above the default has the effect of smoothing the response curve, thereby reducing the number of parameters in the model. Regularization is a common approach in model selection to balance model fit and complexity, allowing both accurate prediction and generality (Elith et al. 2011). Maxent uses a default regularization setting of 1.0, which is derived for a given set of training sites and designed to achieve this balance (see Elith et al. 2011 and Phillips and Dudik 2008 for a thorough examination of the regularization settings). A regularization setting less than 1.0 produces an output distribution that is a closer fit to the training sites but which can result in overfitting, and values greater than 1.0 will provide a more spread out, less localized prediction (Phillips, n.d.). Based on our initial model evaluations, we used Maxent's default regularization value of 1.0 in the models reported here.

High-Severity Disturbance Mask

To exclude some areas of unrealistic output in our Maxent model, such as exaggerated forest growth, we applied cumulative high-severity disturbance masks to our nesting habitat maps before estimating acres of habitat or conducting further analyses. These masks were produced for the NWFP Monitoring Program and used for the northern spotted owl and late-successional and old-growth forests 25-year status and trend reports. First, forest disturbances across the NWFP area were categorized into low, medium, and high severity on an annual basis from 1986 to 2017 (Davis et al. n.d.). The disturbance values were then summed from 1986 to 1993 (for the 1993 mask) and from 1986 to 2017 (for the 2017 mask) and recategorized based on the new cumulative values. Areas that ranked as high-severity disturbances were used to produce a 1993 and 2017 high-severity disturbance mask. We then overlaid these masks on our 1993 and 2017 maps of murrelet higher probability nesting habitat. We used them to mask out habitat that was projected within areas of high-severity disturbances. In other words, masks were used to exclude "higher probability" nesting habitat pixels in the 1993 and 2017 maps that the high-severity disturbance mask indicated had undergone a high-severity disturbance, and thus were unlikely to have habitat. For example, this approach was used to capture delayed fire mortality, the effects of which can be spread over several successive years.

Summarizing Maxent Output

We ran separate Maxent models for each murrelet model region (WASH, ORCO, CAKL) using the GNN covariates and nest sites described above. We ran Maxent using 25 replicated model runs; each produced a map of 1993 habitat probability. During each of the 25 model runs, Maxent randomly partitioned the nest sites into two bins: (1) 75 percent of nest sites were used to train the model (the remaining 25 percent of nests were withheld from this process), and (2) 25 percent of nest sites were used for testing the performance of the resulting model. We used this approach because model iterations with randomly partitioned presence sites provided data to assess the average behavior of the models and allowed us to assess model performance (see "Results—Model Performance" below). Because the presence sites were randomly repartitioned for each of the 25 replicate model runs, the resulting models and maps differed among the replicates. Thus, for each model region, Maxent generated 25 different maps of habitat probability for 1993. The Maxent modeling platform also produced maps with the habitat probability scores averaged across the 25 replicates for each model region for 1993. To estimate 2017 conditions, the average 1993 model from each murrelet model region was projected onto 2017 covariate values, creating a single map of 2017 habitat probability for each model region.

The primary output from the Maxent model is a relative probability of occurrence (of a murrelet nest) for each pixel in the model region based on "cloglog" output from Maxent. In other words, Maxent generated a map that provided an estimate between 0 and 1 of the probability of a murrelet nest per pixel. To reiterate, this map is based on the averaged 25 model runs described in the preceding paragraph. For estimating acres of nesting habitat and habitat change over time, we converted this average map to three levels of probability. To do this, we followed the methods described in Raphael et al. (2016) to generate thresholds separating lower, moderate, and higher probabilities of nesting. We used the point where the ratio of predicted probability of presence versus expected probability of presence (P/E) = 1.0 (that is, where the predicted frequency of test sites equals the expected frequency of test sites) as a threshold to separate higher and moderate habitat probability from lower probability. For pixels above the P/E threshold, we then computed the mean probability score for all nest locations used for modeling in that region and used that mean to separate the two higher classes of habitat probability (fig. 4). Thus, we created three levels of habitat probability:

- **Lower probability:** all pixels with probability values below the P/E = 1 threshold. This corresponds with classes 1 and 2 in Raphael et al. (2016).
- **Moderate probability**: all pixels with probability values between the P/E = 1 threshold and the mean logistic score for all nest locations used for modeling in that region. This corresponds with class 3 in Raphael et al. (2016).

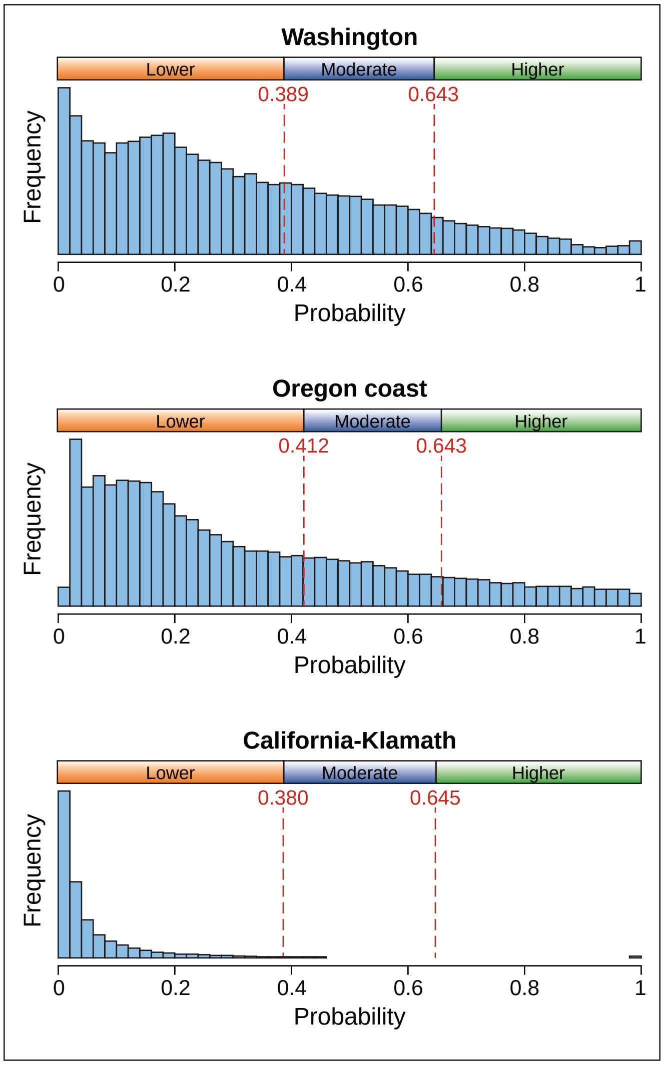

Figure 4—Frequency distribution of Maxent scores (probability of nesting habitat) in each the three model regions in 1993 by frequency distribution level and separated by thresholds as defined in this report. In subsequent tables and figures, the higher probability bin denotes our best representation of marbled murrelet nesting habitat.

- **Higher probability**: all pixels with logistic probability values greater than the mean value at nest locations in each region. This corresponds with class 4 in Raphael et al. (2016).

Each murrelet model region had a different set of thresholds because each model region was run separately in Maxent. Thresholds were based on the 1993 model outputs, and within each model region the same set of thresholds were used for both the 1993 and 2017 maps.

We computed confidence intervals using a map of the standard deviation produced by Maxent. We multiplied this map by 2.064/sqrt(25), where 25 indicates the number of repetitions for each Maxent run. The constant 2.064 represents the critical t value for a 95 percent confidence interval with 24 degrees of freedom (df) (where df = *n* - 1). The resulting values were both subtracted from and added to the mean map to obtain lower and upper confidence interval maps. We then estimated the number of acres above our threshold on these confidence interval maps.

Forested areas that were modeled as higher probability were carried forward in our analysis as murrelet nesting habitat. Thus, for the purposes of this report, "nesting habitat" is defined as areas classified as "higher probability." We summarized the probability of nesting habitat for the entire NWFP area and then by state, conservation zone, and landowner.

Refining Habitat Probability Definitions—MSPA

Within higher probability nesting habitat, habitat quality varies. Distance to edge is likely a major factor that can influence murrelet nesting habitat quality (et al. 2018). Murrelets are susceptible to nest depredation from corvids, including jays and ravens (Hébert and Golightly 2007, Golightly and Schneider 2011, Singer et al. 1991), which are associated with edge habitats and fragmented stands in this region (Marzluff et al. 2004, Marzluff and Neatherlin 2006, Vigallon and Marzluff 2005). Previous research with natural and artificial murrelet nests indicated that nests within 50 to 60 m (164 to 197 ft) of edge are most susceptible to depredations and nest failure (Malt and Lank 2007, 2009; Nelson and Hamer 1995; Raphael et al. 2002). Van Rooyen et al. (2011) also found that murrelet nest sites at timber harvest edges had lower moss abundance than interior and natural-edge nest sites (stream corridors and avalanche chutes) due to stronger winds, higher temperature variability, and lower moisture retention. Moss is an important nest substrate for murrelets, and we assumed that edge habitat is poorer in quality compared to interior forest tracts (see Raphael et al. 2018).

To account for the negative effects of edge habitat and habitat fragmentation on this species, we used morphological spatial pattern analysis (MSPA) to refine our classification of higher probability nesting habitat into "core" (large tracts of fragmented, contiguous habitat), "edge" (60-m-wide strip surrounding all contiguous tracks of core habitat), and "scatter" (smaller scattered and isolated higher probability patches that are not large enough to contain core habitat and are suboptimal murrelet nesting habitat) (fig. 5). Given what is known of the nesting ecology of murrelets at this time, we assumed that core provided the best quality habitat, where nest failure would be lowest and moss for platforms more abundant, followed by edge because it at least abutted core on one side, though murrelets would presumably experience higher predation pressure along an exposed forest edge. We assumed that scatter represented the poorest quality habitat because it was comprised of small patches. While many configurations are possible when projecting such rules on the landscape, in general, all scattered pixels are within 60 m of nonhabitat and most susceptible to nest failure and drying effects that reduce moss abundance.

We used the software GUIDOS (Soille and Vogt 2008, Vogt and Riiters 2017) to conduct this analysis. Our settings were similar to Raphael et al. (2016) in that our MSPA analysis included an 8-cell connectivity rule (i.e., diagonal connections were allowed when assigning pixels to habitat patches) and the "intext" option was enabled (combinations of classes were allowed). Following Davis et al. (n.d.), we disabled transitions in our 25-year analysis, which effectively simplified the classification of edge around core habitat by forcing all habitat bounding core by 60 m (the width of two 30-m pixels) to be classified as edge. In the

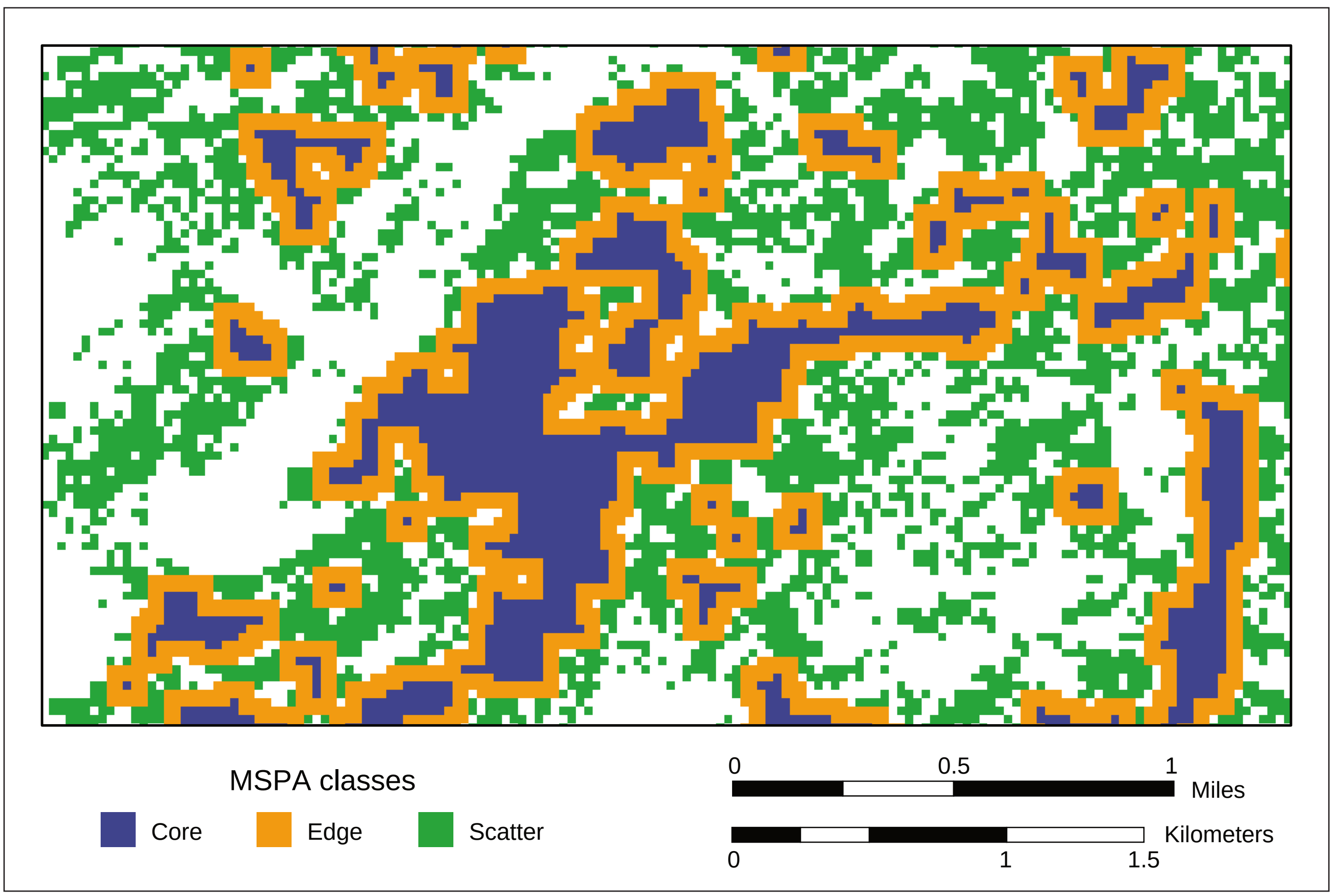

Figure 5—An example of morphological spatial pattern analysis (MSPA) used to distinguish fragmented habitat (scatter) from contiguous blocks of core habitat, which are surrounded by 197 ft (60 m) of edge on all sides.

end, this did not differ from Raphael et al. (2016), in which transitions were enabled, because all transition elements in both the 20- and 25-year reports were reclassified into the edge category for simplification.

In summary, we grouped all MSPA classes into the following three habitat classes:

Core: (included MSPA "core" habitat class) represented higher probability nesting habitat that was farther than 60 m from the edge of nonhabitat. The minimum patch size for core habitat was 5.56 acre (2.25 hectare). This represents the highest quality nesting habitat.

Edge: (included MSPA "bridge in perforation," "bridge/edge," "edge," "loop in edge," "loop in perforation," and "perforation") represented higher probability nesting habitat that adjoins core habitat on one side, but which may make murrelet nests more susceptible to failure than core habitat because it is bounded by nonhabitat on at least one side. This represents habitat of intermediate quality.

Scatter: (included MSPA "branch," "bridge," "loop," and "islet") all isolated pixels of higher probability nesting habitat that were too small or narrow to contain core habitat. This represents fragmented patches that are the poorest quality habitat for murrelets because nests are the most vulnerable to predation.

Measuring Habitat Change and Attributing Causes of Habitat Loss

To estimate the change in higher probability nesting habitat since the start of the NWFP, we compared the amount of habitat at our two bookend years, 1993 and 2017. We estimated the net change in higher probability nesting habitat over this time period, which represented the difference between area of nesting habitat gains (increases in higher probability nesting habitat from 1993 to 2017) and losses (decreases in higher probability nesting habitat from 1993 to 2017). To test for the statistical significance of the magnitude of change by state, conservation zone, and landownership, we performed matched-pair t-tests using each of the 25 replicates as samples and testing the mean difference between amounts of higher probability nesting habitat in 1993 versus the amount in 2017 across each replicate. Based on a recommendation from the GNN team, we used a "noise-reduction" approach, whereby any change in classification (gain or loss) to patches of 1 acre (5 pixels) or less were considered noise and were reverted to 1993 values.

We also overlaid remotely sensed data on forest disturbances on all habitat losses and assigned a cause of loss, or disturbance agent, to lost pixels. For this analysis, we obtained LCMS forest disturbance data for each year, 1993 to 2017, for our analysis area. LCMS disturbance models are similar to the LandTrendr models (Healey et al. 2008) used in the 20-year report (Raphael et al. 2016), but take advantage of ensemble modeling (Kennedy et al. 2012) in which map accuracy is improved by using a collection of models built on different spectral bands (Cohen et al. 2018, Healey et al. 2018). For a detailed description of this approach, refer to Davis et al. (n.d.). We computed the acres of habitat lost to one of four disturbance agents (see below) using annual LCMS maps and used this data to construct figures showing nesting habitat loss attributed to timber harvest, wildfire, and insect damage for each year, 1993 to 2017. In this analysis, it is important to note that the year of detection does not always represent the year a disturbance occurred. Often, vegetation change caused by a disturbance was detected in the following year, but sometimes it was detected after >1 year, depending on Landsat image availability and other factors (Davis et al., n.d.). For example, canopy loss from wildfire sometimes was not detected from satellite imagery until the year after a fire occurred. Moreover, imagery was obtained in late summer (July to September) rather than at the change in the calendar year (December to January). Thus, some 2017 fires were excluded from our analysis, such as the Chetco Bar Fire, which occurred in late summer in 2017.

We also obtained a layer of cumulative LCMS disturbances from 1993 to 2017. For this cumulative map, some pixels had more than one disturbance; in those cases, we used the highest magnitude of disturbance from the 1993–2017 time series. We overlaid this cumulative, bookend LCMS disturbance map on our bookend map of nesting habitat losses to compute acreage of habitat lost in each disturbance category over the entire 25-year period. These estimates were highly correlated with the "annual" analysis described in the preceding paragraph, but we felt they were more representative in estimating the loss of murrelet habitat in different categories because they eliminated some double counting of pixels.

All of the disturbance maps we obtained grouped disturbances into four types: timber harvest, wildfire, insect damage, and other natural disturbances. Assignment of cause agent was based on interpretation of the duration of the disturbance; location relative to federal land use allocations; relationship to aerial detection survey maps for insects and disease (Coleman et al. 2018, Johnson 2016); spatial relationship to mapped wildfire perimeters (e.g., GeoMAC, National Interagency Fire Center, Monitoring Trends in Burn Severity), and when inside wildfire perimeters, the year of detection relative to the wildfire year (Davis et al. n.d.. The causes of attribution are summarized by Davis et al., (n.d.) as follows:

- Timber harvest—Disturbance was classified to the timber harvest category if they were short-duration (<4 years) events outside of congressionally reserved (CR) lands (e.g., wilderness areas) where timber harvesting is not allowed in the reserved area's management plan. Over the NWFP monitoring time period, new CRs have been designated by Congress. For these, we applied harvest attribution only to disturbances prior to the year of designation. Abrupt disturbances within wildfire perimeters were attributed to harvesting if they occurred prior to the fire year. Similar to Raphael et al. (2016), some short-duration blowdown events and landslides may be erroneously assigned to the timber harvest category in the 25-year analysis, although the magnitude of this error is expected to be less than in previous monitoring reports because of the annual accounting of disturbance.
- Wildfire—Pixels with disturbances were assigned to the wildfire category if their duration was 1 year and they occurred the same year, or the year following, the fire year within a mapped wildfire perimeter.
- Insect and disease—This category was used for long-duration (≥4 years) disturbance events, or where more than four disturbances were detected for a pixel. It was also used for small, shorter duration disturbances (patch size <9 pixels) when they occurred within a potential insect/disease area (PIDA) (Davis et al., n.d.). The PIDA was generated using a focal mean analyses on a binary map of pixels exhibiting persistent or chronic disturbance signals (duration ≥4 years or >4 disturbance events). A focal mean using a 1-km radius (equivalent to a 776-acre area) was compared with aerial detection survey polygons for the region to identify a mapping threshold to represent PIDAs. Davis et al. (n.d.) observed that when at least 10 percent of this area contained persistent/chronic disturbance signals, it matched well with the aerial detection survey data.
- Other disturbance—All detected disturbances not assigned above. This category included blowdowns, floods, and landslides.

Last, we computed the acreage of lost higher probability nesting and core habitat for which LCMS did not assign a disturbance type, or the acres of unattributable loss.

Effects of Human Disturbance

Murrelet nests are sensitive to human modification of landscapes. Human activities directly impact murrelets in many ways, such as when trees containing nesting platforms are harvested, or when powerlines are constructed across flyways that murrelets use to access nesting habitat. Examples of ways in which humans indirectly impact murrelets include the creation of edge habitats near older forests, which can attract nest predators, such as jays and ravens, and the provisioning of food subsidies for these nest predators at backyard bird feeders, campgrounds, picnic areas, landfills, and along roadways.

To assess human impacts to murrelet nesting habitat, we quantified human landscape modification based on a human footprint model that included information on human impacts to the landscape. We compared four models of human footprint for our analysis area before choosing one for this analysis: Leu et al. (2008), Theobald (2013), Venter et al. (2016), and Hak and Comer (2017). In the end, we decided to use a human footprint model created by Theobald (2013) because it covered our entire study area, was generated at an adequate spatial resolution (295 ft, or 90 m), contained model inputs relevant to murrelet nesting (including residential density, roads, forest cover types, and powerlines, among other factors), and contained relatively recent data inputs. Theobald (2013) ranked human footprint on a scale of 0 to 1, with 0 representing areas with no human impacts and 1 representing areas of extremely high impact, such as interstate highways and the centers of large metropolitan areas. To determine how the degree of human modification of the landscape differed between different habitat classes (core, edge, and scatter), and for different portions of the murrelet range, we calculated the mean human footprint of higher probability nesting habitat pixels in each of these classes by state and landowner. We compared these estimates to the mean human footprint for habitat-capable lands not modeled as higher probability nesting habitat (i.e., areas with open canopied forests, high amounts of hardwoods, and small-diameter trees). We computed mean human footprint rank for higher probability nesting habitat and core, edge, and scatter for 2017 to describe the impacts of human activities at the most recent time period in our analysis.

Relationship Between Nesting Habitat and Populations

While the focus of this report was to estimate acres of higher probability nesting habitat, we were also interested in comparing the amount of nesting habitat to the size of nearby murrelet populations from at-sea surveys reported in McIver et al. (2021). We used data on the mean number of murrelets by state and conservation zone from 2013 to 2017, plotted against mean acres of higher probability nesting habitat from 2017. We also compared the trend in murrelet populations with the trend in higher probability nesting habitat from 1993 to 2017. For these comparisons, we estimated the annual rate of change in murrelet numbers using data from 2001 to 2017 for Washington and conservation zone 2; data from 2000 to 2017 for Oregon, California, and conservation zones 4 and 5; and data from 2001 to 2016 for conservation zones 1 and 3 (McIver et al. 2021). We included 95 percent confidence intervals for all means using methods described above for amount of habitat in 2017. Confidence intervals on habitat change were based on the full set of 25 replicated model runs. We computed the mean change in higher probability nesting habitat (1993 to 2017) for each Maxent model replication, and then calculated the confidence interval from that set of 25 estimates.

Results

Summary of Covariate Values

For most covariates, mean values were higher for nests sites compared to mean values across habitat-capable lands (table 4). Two exceptions were CANCOV_HDW and MULTISTORY_50, both of which were lower at nest sites in some model regions. Canopy cover of hardwoods, which was included in the CAKL model region only, was lower at nest sites. This was expected because murrelets select coniferous forests for nesting. MULTISTORY_50 was lower at nest sites in both ORCO (only marginally lower) and CAKL model regions and may indicate murrelet use of stands with simpler stand structure in the southern portion of their range.

We present estimates of the relative contribution of each covariate to the final Maxent model in table 5. These values are estimated by Maxent during the model optimization process and are based on the increase in training gain associated with each covariate. They indicate the relative importance of covariates in building the Maxent model in each model region. The contribution values should be interpreted with caution for covariates that are highly correlated because there is an element of chance in how the percentage of contribution is divided among highly correlated covariates. For highly correlated covariates, one may be assigned a high contribution and the other a low contribution when in fact both may be important to the species.

Overall contributions of the covariates show that CANCOV_CON, MNDBHBA_CON, and DDI made the greatest contributions to the WASH model; STANDHT, CANCOV_CON, and QMDC_DOM were the strongest in the ORCO model; and CANCOV_CON and SESE_BA_GE were the strongest in the CAKL model (table 5). Combining the results from tables 4 and 5 and focusing on the covariates with the greatest model contributions, nest sites had, on average, much higher values for influential covariates. In Washington, CANCOV_CON and MNDBHBA_CON were 85 percent and 73 cm at nest sites, respectively, compared to 65 percent and 39 cm for all habitat-capable lands. For the ORCO model region,

Table 4—Mean, standard deviation (SD), minimum, and maximum values for gradient nearest neighbor covariates used in Maxent analysis for murrelet nest sites in 1993, compared to all habitat-capable lands in 1993 and 2017, by murrelet model region

Model region	Covariate[a]	Nest sites (1993)				All habitat-capable lands (1993)				All habitat-capable lands (2017)			
		Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
		n = 59				n = 10,849,312 acres[b]				n = 10,849,312 acres[b]			
Washington (WASH)	AGE_DOM_NO_REM	195	111	28	431	93	95	0	710	93	93	0	710
	CANCOV_CON	85	9	54	98	65	28	0	100	66	27	0	100
	DDI	619	184	147	967	394	231	0	998	409	217	0	998
	MNDBHBA_CON	73	30	14	150	39	25	0	194	41	24	0	194
	MULTISTORY_50	59	24	8	99	43	28	0	100	43	28	0	100
	QMDC_DOM	60	22	13	103	35	23	0	166	38	22	0	165
	STNDHGT	32	10	8	53	20	11	0	66	22	10	0	65
		n = 75				n = 5,646,455 acres[b]				n = 5,646,455 acres[b]			
Oregon Coast (ORCO)	AGE_DOM_NO_REM	110	57	37	261	59	48	0	498	67	52	0	499
	CANCOV_CON	68	19	10	92	57	26	0	98	54	26	0	98
	DDI	562	141	172	868	364	202	0	987	392	205	0	986
	MNDBHBA_CON	75	27	28	131	41	28	0	209	48	33	0	161
	MULTISTORY_50	24	17	1	95	25	20	0	100	26	18	0	100
	PISI_BA_GE_13	3	8	0	49	1	5	0	86	1	4	0	87
	QMDC_DOM	71	27	18	126	36	26	0	156	44	31	0	150
	STNDHGT	38	11	11	60	21	13	0	72	24	13	0	72
		n = 73				n = 4,213,082 acres[b]				n = 4,213,082 acres[b]			
California-Klamath (CAKL)	CANCOV_CON	89	17	16	99	51	26	0	100	53	26	0	100
	CANCOV_HDW	20	18	1	74	43	28	0	97	43	26	0	97
	DDI	693	157	148	940	484	194	0	996	489	191	0	999
	MULTISTORY_50	58	24	13	94	66	24	0	100	65	25	0	100
	SESE_BA_GE_13	89	48	0	209	11	24	0	212	9	21	0	210
	STNDHGT	40	14	7	62	19	9	0	65	20	9	0	65

[a] Descriptions of the covariates and units are in table 2.
[b] Represents analysis area in murrelet inland zones 1 and 2 in WASH and murrelet inland zone 1 in ORCO and CAKL..

STANDHT and CANCOV_CON were higher at nest sites (38 m and 68 percent at nest sites, and 21 m and 57 percent for all habitat-capable lands). Likewise, for the CAKL model region, CANCOV_CON, and SESE_BA_GE were higher at nest sites (89 percent and 89 m^2/hectare at nest sites and 51 percent and 11 m^2/hectare for all habitat-capable lands).

Response curves showing Maxent scores for each of the covariates (fig. 6) demonstrated that the most influential covariates had positive relationships (increasing values of the covariate with increasing Maxent scores). Another way to evaluate contributions of our individual covariates is to compare training gain of each covariate modeled alone against the gain from the global model (when all covariates are included) and to compare the effect on global gain when that covariate is removed and all other covariates are retained (fig. 7). Evaluated in this way, strong covari-

Table 5—Covariate percentages of contribution to nesting habitat Maxent model in each murrelet model region of this report; see text for details about potential effect of correlations on reported importance values

Washington (WASH)		Oregon coast (ORCO)		California-Klamath (CAKL)	
Covariate	Covariate importance (%)	Covariate	Covariate importance (%)	Covariate	Covariate importance (%)
CANCOV_CON	31.9	STNDHGT	34.5	CANCOV_CON	46.3
MNDBHBA_CON	24.6	CANCOV_CON	21.4	SESE_BA_GE_13	25.0
DDI	20.6	QMDC_DOM	14.5	MULTISTORY_50	12.0
STNDHGT	8.9	DDI	12.1	STNDHGT	10.2
QMDC_DOM	7.5	MULTISTORY_50	7.6	DDI	4.4
AGE_DOM_NO_REM	3.8	MNDBHBA_CON	5.9	CANCOV_HDW	2.1
MULTISTORY_50	2.7	AGE_DOM_NO_REM	2.3		
		PISI_BA_GE_13	1.7		

ates in the WASH model region were DDI, STND_HGT, and QMDC_DOM (based on loss of gain for models run without these covariates) and MNDBHBA_CON (based on gain of models with only this covariate). In the ORCO model region, strong contributors were DDI, MND-BHBA_CON, and QMDC_DOM (without covariate) and STNDHGT (with only this covariate). In the CAKL model region, CANCOV_HDW, DDI, and SESE_BA_GE_13 were influential in models run without the covariate (i.e., a lot of gain would be lost if these covariates were excluded), and STNDHGT and SESE_BA_GE_13 were influential in single-covariate models.

Maxent Model Performance

We used several metrics to assess model performance. First, we compared test gain and training gain to evaluate model fit. If our models were overfit (i.e., with an overabundance of parameters) training gain would to be much larger than test gain. For all murrelet model regions, test gain and training gain were similar and showed overlapping confidence intervals (fig. 8). This indicates that the model was robust when challenged with data that were not part of the model-building process. Gain also indicates how markedly the model distinguishes the presence samples (nest sites) from the background, using the equation e^{gain} (or exp[gain]), where e ≈ 2.718. For example, if the gain is 2, it means that the average likelihood of all the presence samples is exp(2), or about 7.4 times higher than that of a random background pixel. As measured by test gain, model performance was strongest in the CAKL murrelet model region (gain = 2.268 and exp[2.268] = 9.7) (fig. 8), indicating a stronger distinction between murrelet nest sites and background sites, compared with the other model regions. Test gains were lower in the ORCO murrelet model region (gain = 0.811, exp[0.811] = 2.3) and in Washington (gain = 0.814, exp[0.814] = 2.3). In all regions, test gains appear lower than in the NWFP 20-year analysis (Washington: 1.469, Oregon; 1.634, California; 3.065) (Raphael et al. 2016). However, the 20-year analysis in Raphael et al. (2016) was conducted using state-based model regions that differed slightly from the current murrelet model regions for Oregon and California. While gains can be compared directly for Washington and were lower in this analysis than for the 20-year analysis, direct comparisons of gain are not possible for Oregon and California because murrelet modeling regions differed. Nevertheless, most of Oregon was covered by the ORCO murrelet model region in this report (fig. 3), and performance for this model region was lower than for Oregon in Raphael et al. (2016). We review the implications of this in the discussion. Test AUC values were ranked among the murrelet model regions in the same pattern as gain: AUC was greatest in CAKL (AUC = 0.900) and lower in the models for ORCO (AUC = 0.834) and WASH (AUC = 0.832) (fig. 8).

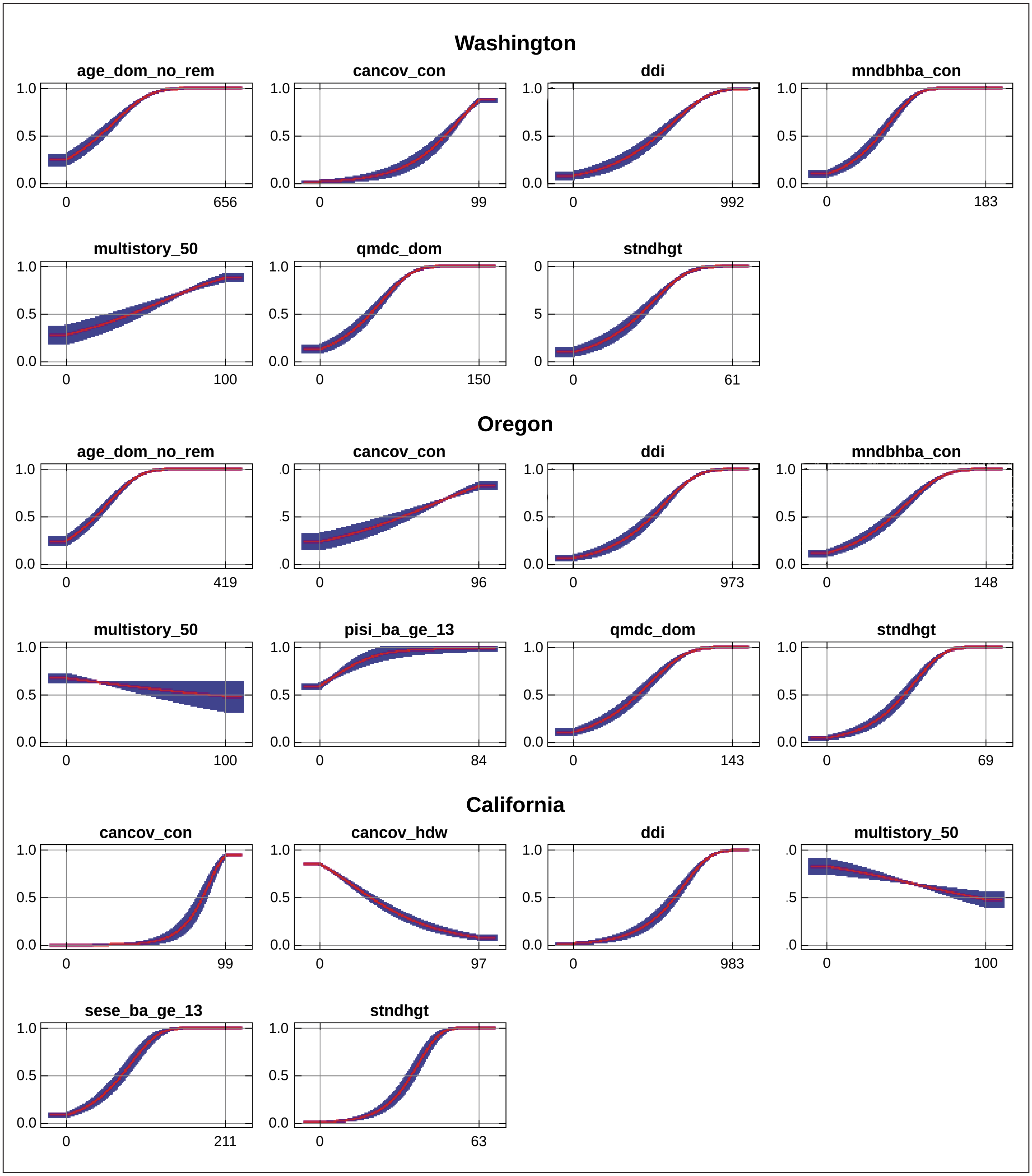

Figure 6—Response curves showing how each covariate affects the Maxent habitat probability score for Washington, Oregon coast, and California-Klamath model regions. The red lines indicate mean response across 25 replicated model runs and blue shading represent 1 standard deviation above and below the mean. The curves show how the habitat probability score (y-axis) changes across the range of covariate values (x-axis) within each model region using a Maxent model with only the corresponding covariate. The curves reflect the dependence of the probability score both on the selected covariate and on dependencies induced by correlations between the selected covariate and other covariates.

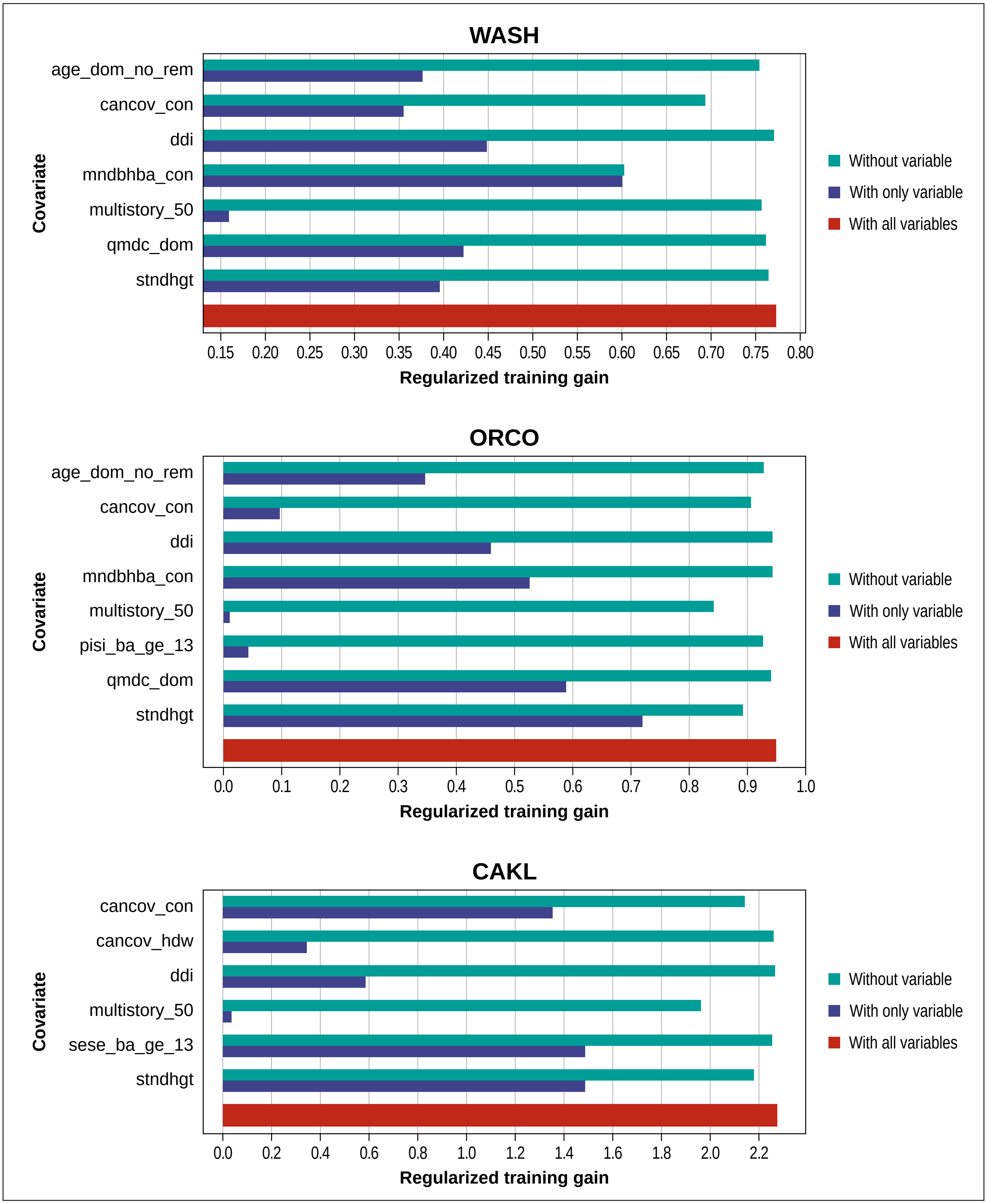

Figure 7—Contributions of environmental covariates to Maxent models of habitat probability for Washington (WASH), Oregon Coast (ORCO), and California-Klamath (CAKL) model regions. The red bar indicates gain from a model with all covariates. The light blue bars indicate the reduction in gain that would occur if that covariate was removed from the model, but all other covariates were included. The dark blue bars indicate gain from a model with only that covariate included.

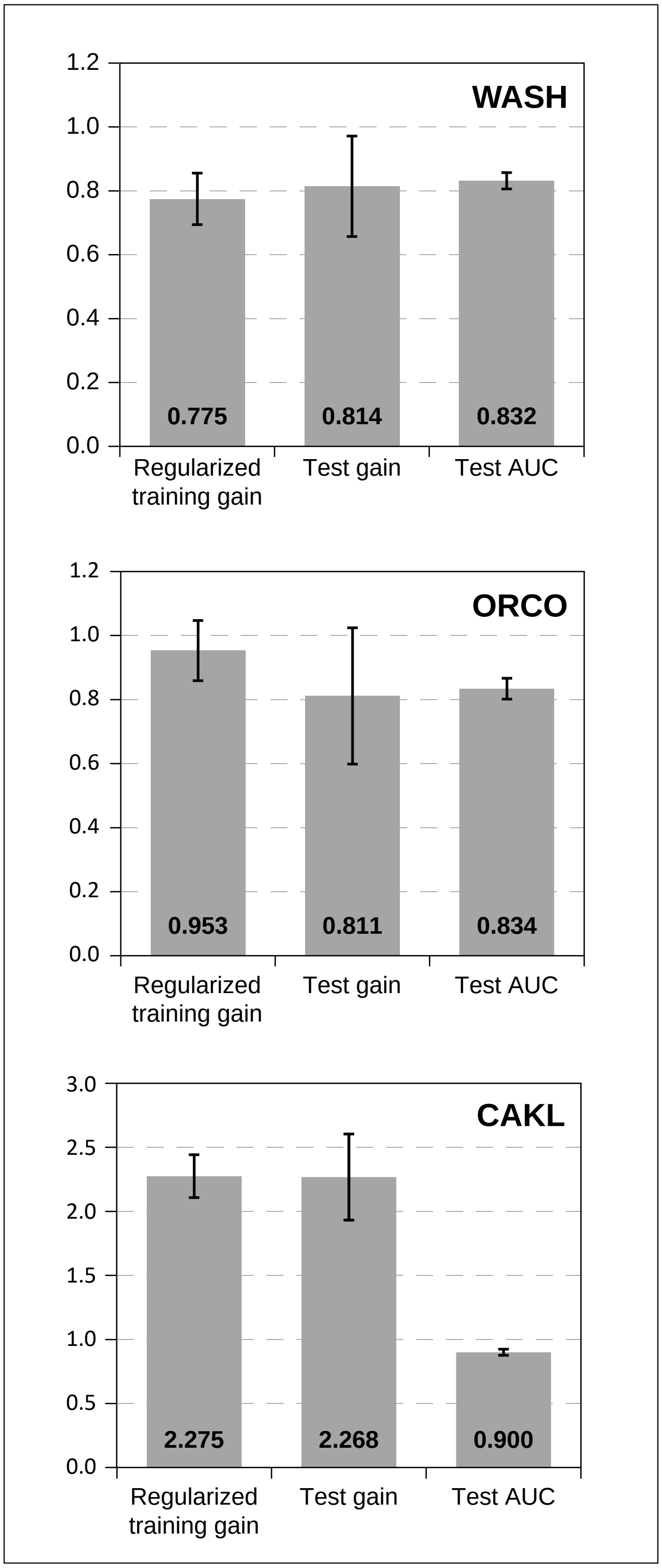

Figure 8—Maxent model performance for Washington (WASH), Oregon coast (ORCO), and California Klamath (CAKL) model regions, including the average training gain, test gain, and test AUC (area under the curve) statistic for 25 model runs, with 95 percent confidence intervals.

Maxent Probability Scores

Probability scores from Maxent provide valuable information on the relative suitability of habitat. This information is lost when we convert the probability score to a simple binary threshold for defining habitat classes. While thresholds were necessary in this report for estimating acres of habitat in different categories (e.g., comparing acres in 1993 to 2017), Maxent probability scores provide a complete, probabilistic map of habitat suitability. Thus, we present maps of Maxent scores (figs. 9 through 11) in addition to maps based on our threshold criteria (figs. 13 through 15). Mean habitat probability scores (table 6) were highest in Washington, lower in Oregon, and lowest in California. We observed similar patterns among the conservation zones. Among landownership categories, federal reserved lands had the highest mean score. Scores on state lands were similar to federal reserved

Table 6—Mean and standard deviation (SD) for Maxent scores for 1993 and 2017 by state, conservation zone (CZ), and landowner (all states and conservation zones combined)

	1993		2017	
	Mean	SD	Mean	SD
State				
Washington	0.308	0.236	0.318	0.237
Oregon	0.216	0.233	0.281	0.254
California	0.065	0.128	0.067	0.121
Conservation zone				
CZ 1	0.298	0.220	0.303	0.217
CZ 2	0.332	0.269	0.362	0.282
CZ 3	0.273	0.247	0.348	0.256
CZ 4	0.075	0.134	0.090	0.152
CZ 5	0.082	0.106	0.091	0.103
Ownership				
Federal reserved	0.330	0.286	0.361	0.278
Federal nonreserved	0.210	0.229	0.266	0.241
State	0.286	0.226	0.316	0.231
Other	0.174	0.183	0.171	0.181
Entire Northwest Forest Plan area	0.237	0.237	0.259	0.244

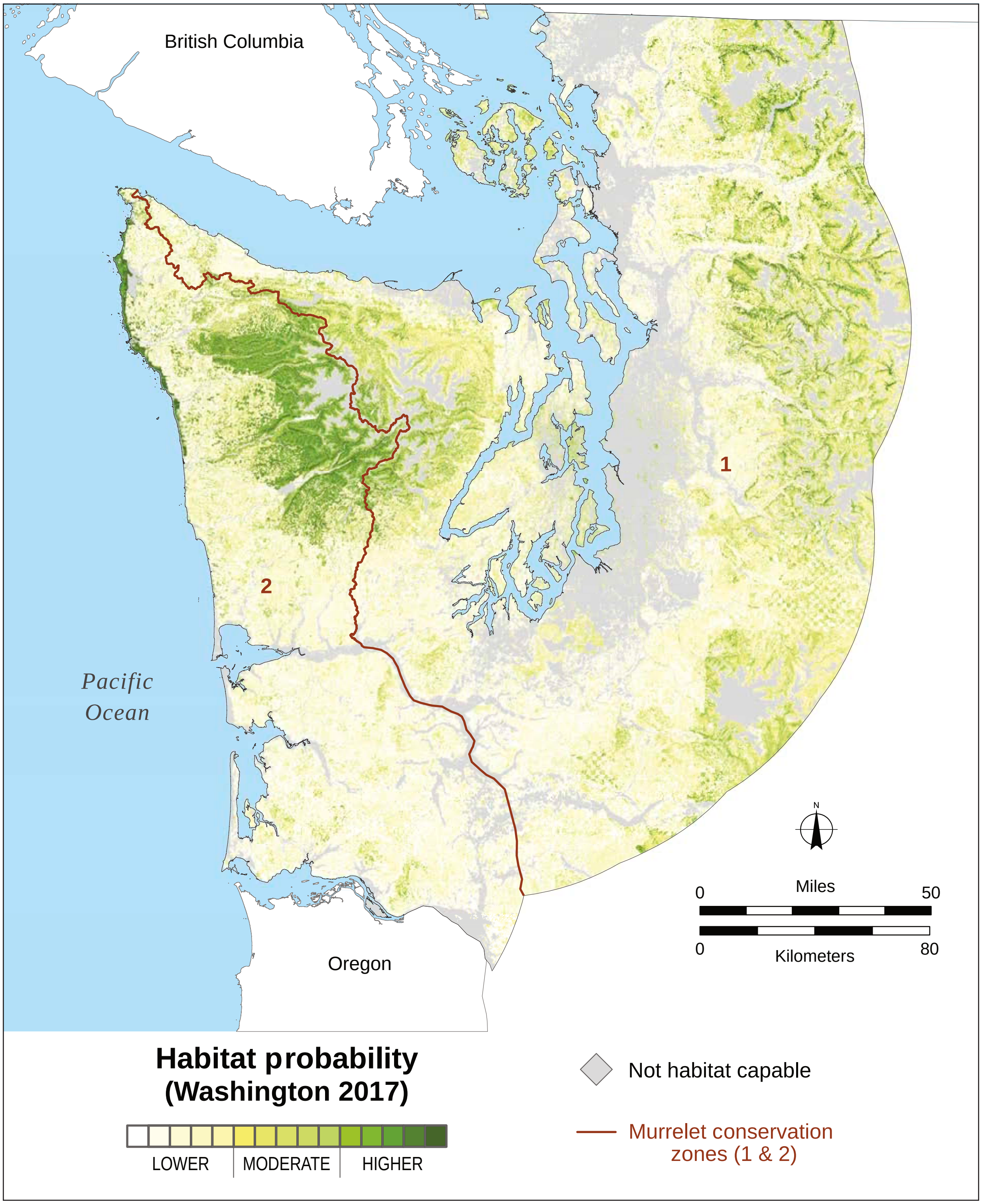

Figure 9—Habitat probability map for marbled murrelet range in Washington for 2017. Colors are separated by lower, moderate, and higher probability of nesting habitat, with probability gradients in each class.

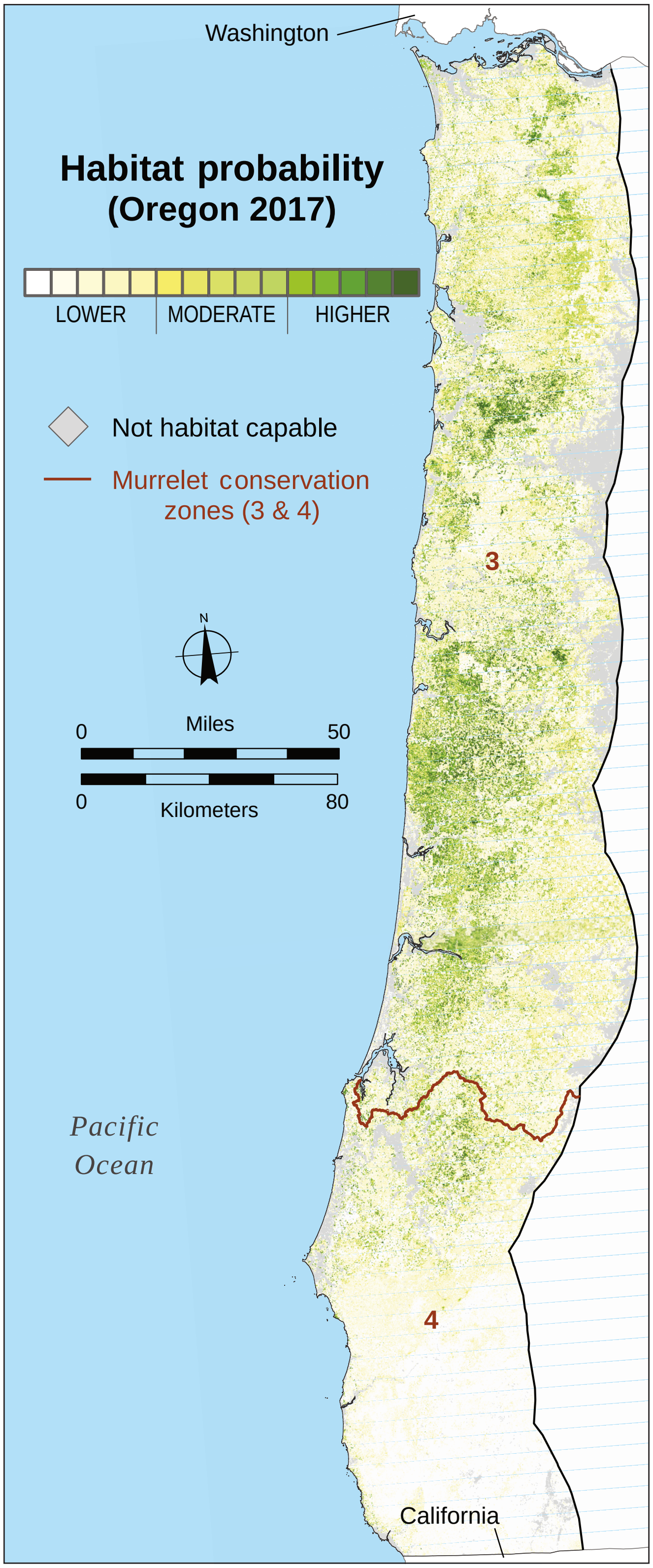

Figure 10—Habitat probability map for marbled murrelet range in Oregon for 2017 by lower, moderate, and higher probability of nesting habitat, with probability gradients in each class.

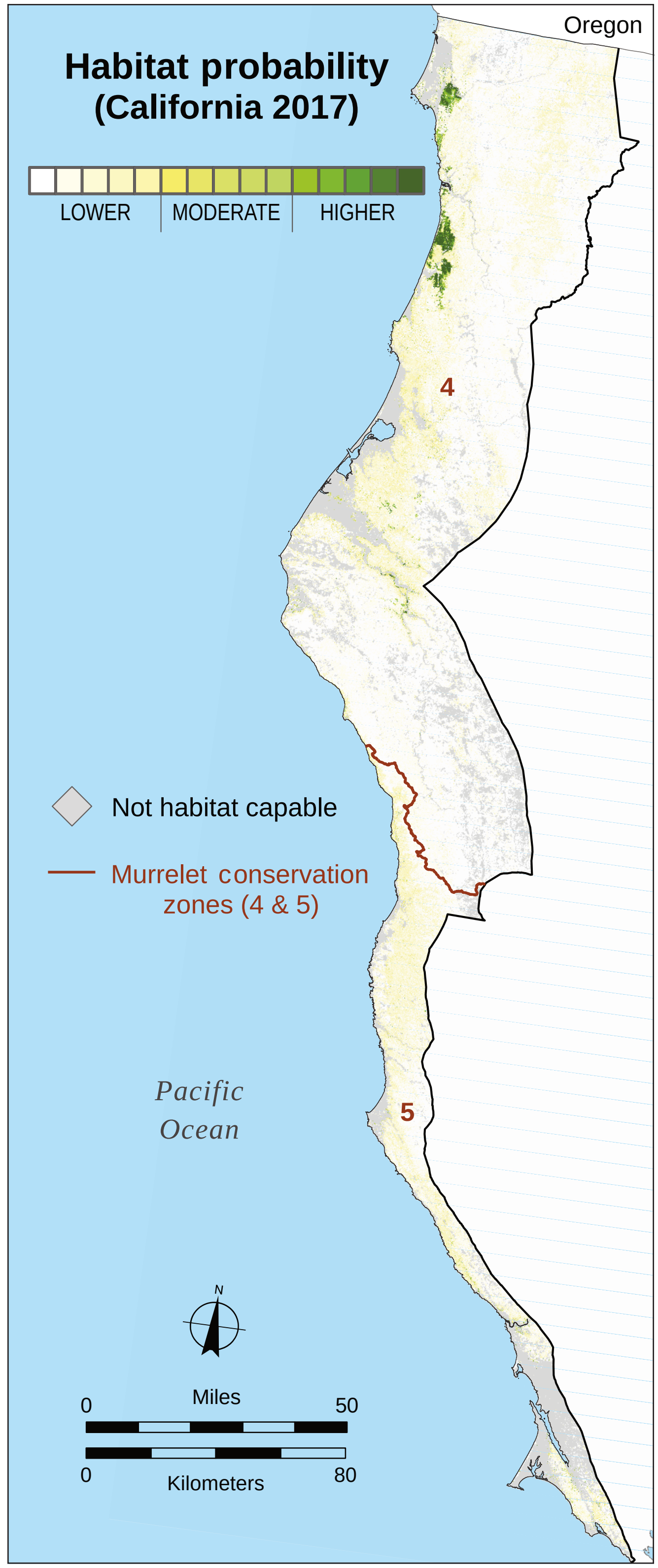

Figure 11—Habitat probability map for marbled murrelet range in California for 2017 by lower, moderate, and higher probability of nesting habitat, with probability gradients in each class.

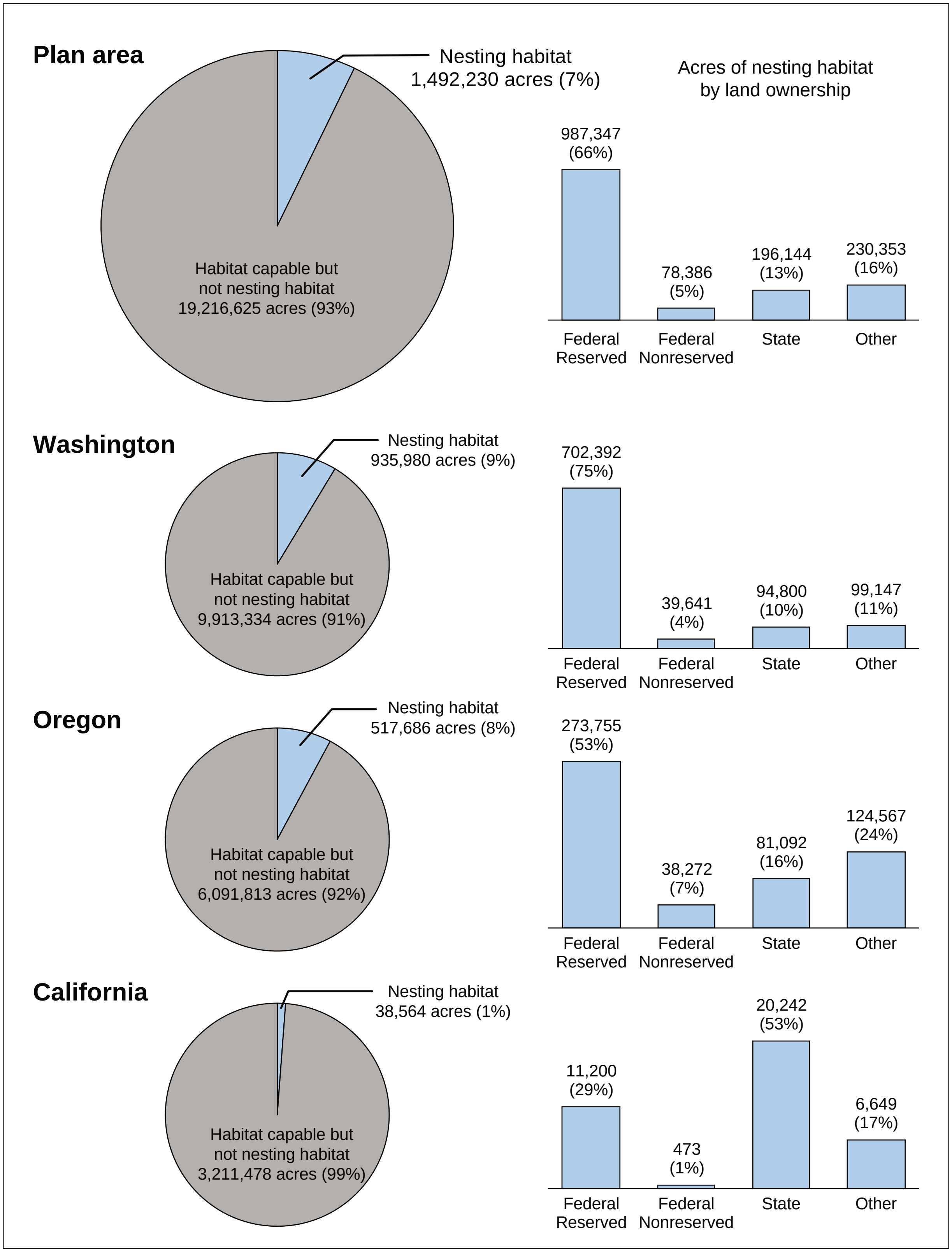

Figure 12—Proportion of higher probability nesting habitat of all habitat-capable lands by landowner in 2017 for our analysis area in Washington, Oregon, and California.

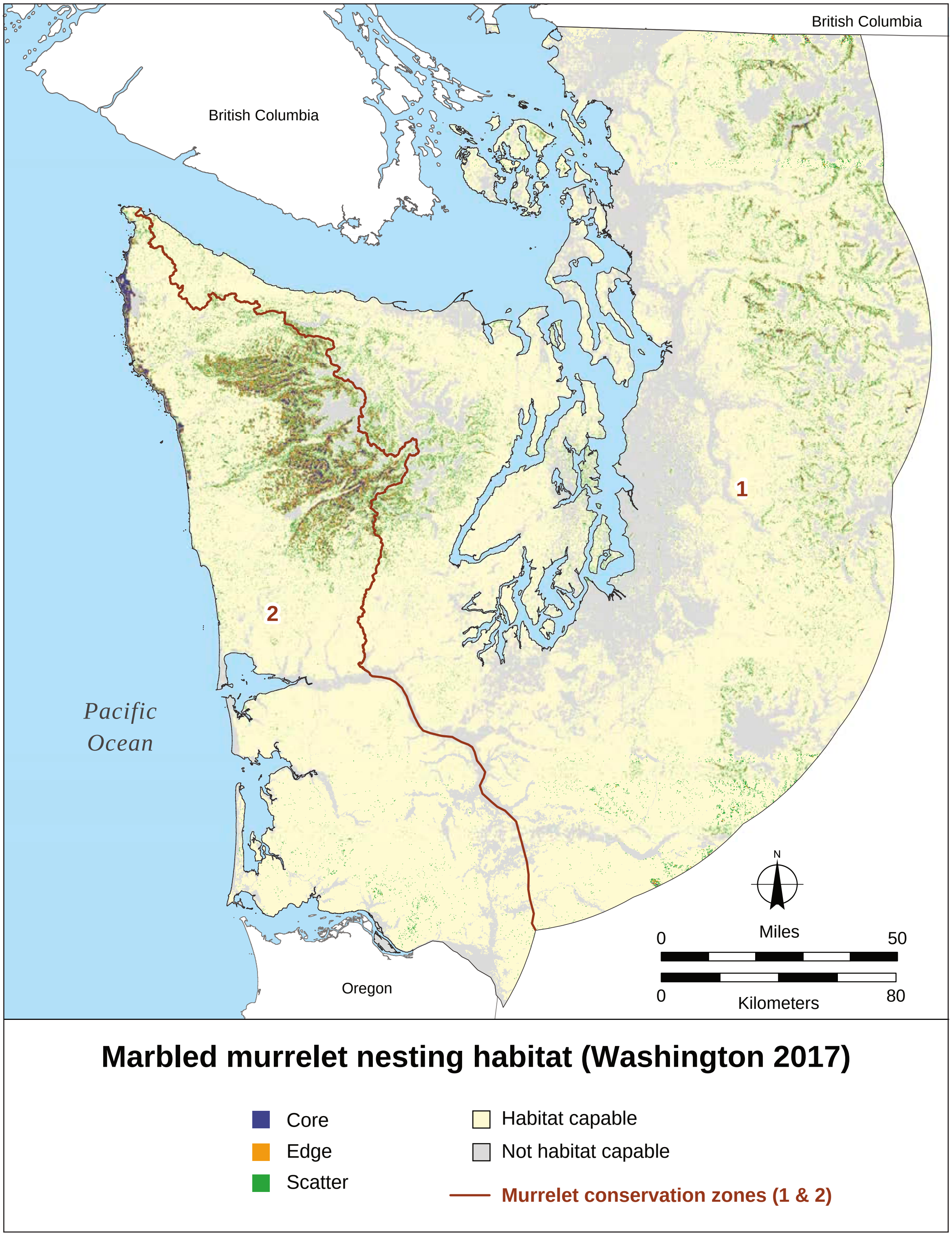

Figure 13—Map depicting higher probability nesting habitat (as depicted by higher probability Maxent score) for murrelets in Washington for the 2017 bookend year, the last year of the modeling period.

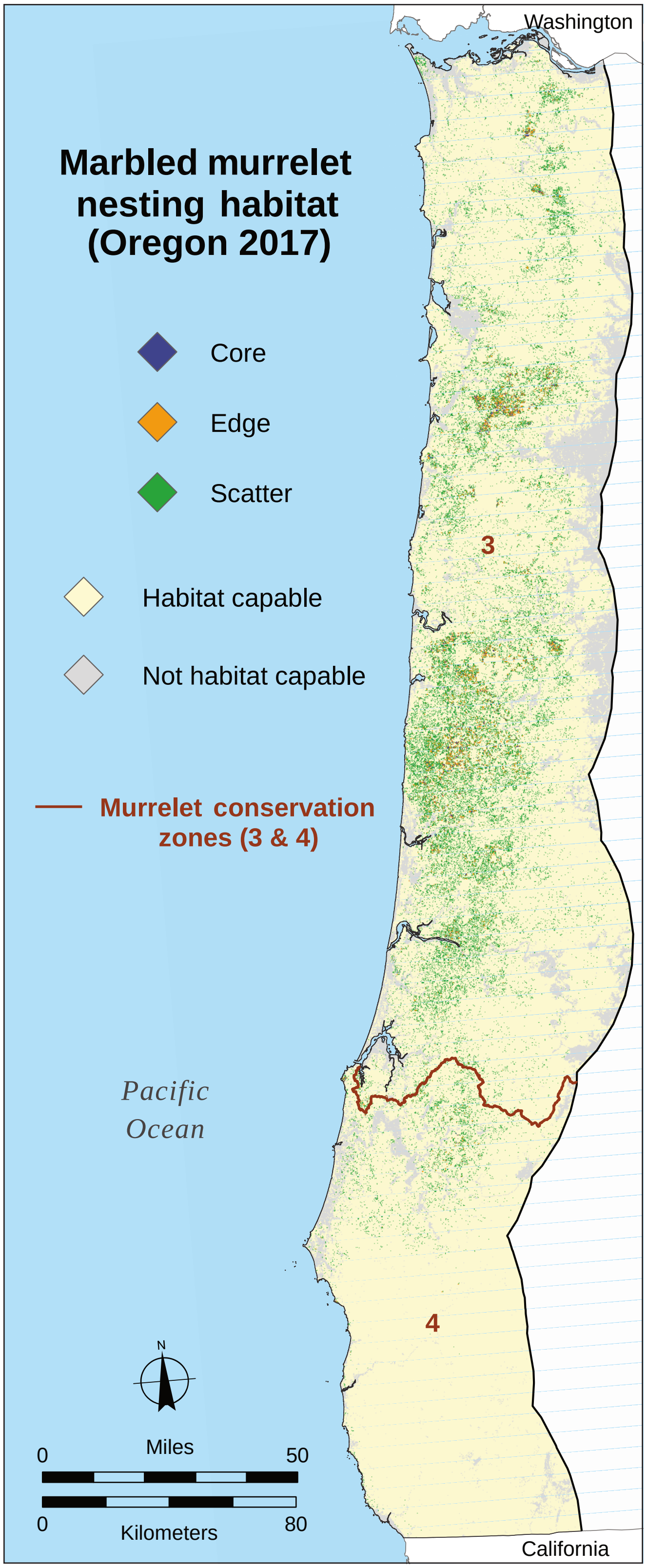

Figure 14—Higher probability nesting habitat (by higher probability Maxent score) for murrelets in Oregon for the 2017 bookend year, the last year of the modeling period.

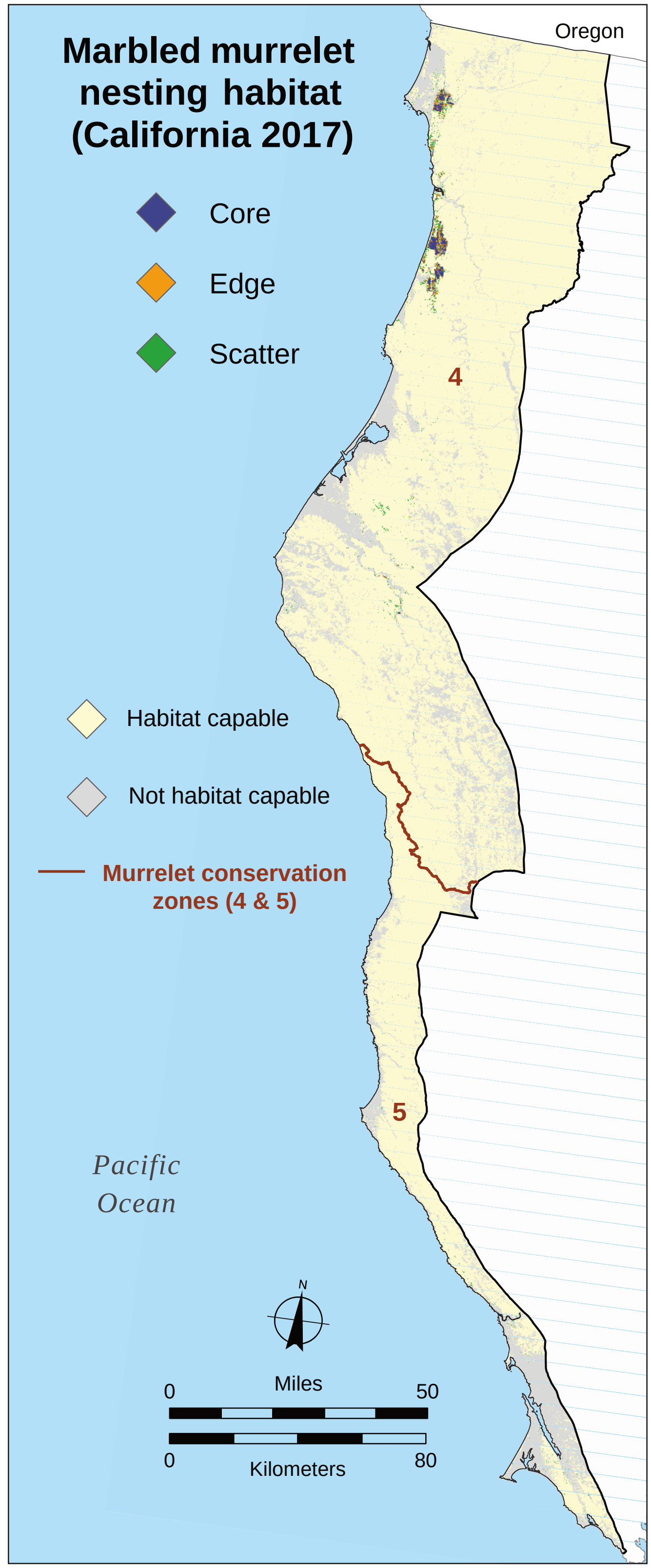

Figure 15—Higher probability nesting habitat (by higher probability Maxent score) for murrelets in California for the 2017 bookend year, the last year of the modeling period.

lands whereas mean score on federal nonreserved lands were next lower. Scores were lowest on other lands (table 6). The mean score increased on state and federal lands, but not on other lands, from 1993 to 2017. Over the portion of the murrelet range modeled, mean score increased by 10 percent from 0.237 to 0.259 between 1993 and 2017 (table 6).

Acres of Nesting Habitat in the NWFP Area

After applying our thresholds, we estimated that there were 1,513,078 acres of higher probability nesting habitat in the NWFP area in 1993 (table 7, figs. 12 through 15). Most higher probability nesting habitat was within federal reserved land use allocations (968,775 acres) (table 7, fig. 12).

Table 7—Acres of lower, moderate, and higher probability nesting habitat by state and landowner for the baseline period (1993) and final year of analysis (2017)

	1993			2017		
State/landowner	Lower probability	Moderate probability	Higher probability	Lower probability	Moderate probability	Higher probability
Washington						
Federal reserved	1,327,727	1,016,831	709,216	1,287,155	1,064,228	702,392
Federal nonreserved	306,865	101,086	38,268	275,401	131,177	39,641
Federal total	1,634,592	1,117,917	747,484	1,562,556	1,195,405	742,033
State	1,246,994	290,022	109,907	1,277,591	274,532	94,800
Other landowners	4,995,937	563,834	142,627	5,231,260	371,990	99,147
Total	7,877,523	1,971,773	1,000,018	8,071,407	1,841,927	935,980
Oregon						
Federal reserved	1,572,290	169,986	248,182	1,472,982	243,721	273,755
Federal nonreserved	403,251	27,630	27,859	365,324	55,144	38,272
Federal total	1,975,541	197,616	276,041	1,838,306	298,865	312,027
State	537,229	101,217	56,539	449,922	163,971	81,092
Other landowners	3,116,361	210,315	138,640	3,114,679	226,070	124,567
Total	5,629,131	509,148	471,220	5,402,907	688,906	517,686
California						
Federal reserved	764,231	7,841	11,377	765,883	6,367	11,200
Federal nonreserved	217,260	234	461	217,222	260	473
Federal total	981,491	8,075	11,838	983,105	6,627	11,673
State	164,909	7,346	20,295	166,055	6,253	20,242
Other landowners	2,015,236	31,145	9,707	2,026,379	23,059	6,649
Total	3,161,636	46,566	41,840	3,175,539	35,939	38,564
Plan area total						
Federal reserved	3,664,248	1,194,658	968,775	3,526,020	1,314,316	987,347
Federal nonreserved	927,376	128,950	66,588	857,947	186,581	78,386
Federal total	4,591,624	1,323,608	1,035,363	4,383,967	1,500,897	1,065,733
State	1,949,132	398,585	186,741	1,893,568	444,756	196,144
Other landowners	10,127,534	805,294	290,974	10,372,318	621,119	230,353
Total	16,668,290	2,527,487	1,513,078	16,649,853	2,566,772	1,492,230

Smaller amounts of higher probability nesting habitat were on other lands (290,974 acres), state lands (186,741 acres), and federal nonreserved lands (66,588 acres) (table 7, fig. 12). Most habitat in 1993 was in scattered fragments on the landscape rather than in continuous blocks of high-quality core habitat. We estimated that 1,129,539 acres were classified as scatter (75 percent) compared with just 140,091 acres (9 percent) of core (table 8).

In 2017, we estimated there were 1,492,230 acres of higher probability nesting habitat in the NWFP area (table 7, fig. 12), of which 137,569 acres (9 percent) were core habitat (table 8). This represents a small net decrease of

Table 8—Distribution of core, edge, and scatter (acres) of higher probability nesting habitat by state and landowner for the baseline period (1993) and final year of analysis (2017)

	1993			2017		
State/landowner	**Core**	**Edge**	**Scatter**	**Core**	**Edge**	**Scatter**
Washington						
Federal reserved	105,372	162,460	441,384	102,787	158,777	440,828
Federal nonreserved	861	3,650	33,757	861	3,687	35,093
Federal total	106,233	166,110	475,141	103,648	162,464	475,921
State	4,020	11,539	94,348	3,892	10,777	80,131
Other landowners	2,352	5,305	134,970	1,915	3,580	93,652
Total	112,605	182,954	704,459	109,455	176,821	649,704
Oregon						
Federal reserved	11,476	39,424	197,282	12,132	41,675	219,947
Federal nonreserved	786	3,117	23,956	1,040	3,965	33,266
Federal total	12,262	42,541	221,238	13,172	45,640	253,213
State	503	2,893	53,143	1,333	4,750	75,009
Other landowners	1,632	6,820	130,188	560	3,169	120,841
Total	14,397	52,254	404,569	15,065	53,559	449,063
California						
Federal reserved	3,700	2,834	4,843	3,694	2,836	4,669
Federal nonreserved	8	46	407	8	40	425
Federal total	3,708	2,880	5,250	3,702	2,876	5,094
State	9,357	5,126	5,812	9,339	5,157	5,746
Other landowners	24	234	9,449	8	112	6,529
Total	13,089	8,240	20,511	13,049	8,145	17,369
Plan area total						
Federal reserved	120,548	204,718	643,509	118,613	203,288	665,444
Federal nonreserved	1,655	6,813	58,120	1,909	7,692	68,784
Federal total	122,203	211,531	701,629	120,522	210,980	734,228
State	13,880	19,558	153,303	14,564	20,684	160,886
Other landowners	4,008	12,359	274,607	2,483	6,861	221,022
Total	140,091	243,448	1,129,539	137,569	238,525	1,116,136

higher probability nesting habitat of -1.38 percent and a net decrease in core habitat of -1.80 percent since the start of the NWFP (table 9). There were some increases in higher probability nesting habitat with the largest net increases occurring on federal reserved lands (18,574 acres) (table 9, fig. 16), and smaller net increases on state lands (9,394 acres) and federal nonreserved lands (11,796 acres). Acres of higher probability nesting habitat increased significantly ($P < 0.05$)

Table 9—Acres of loss, gain and net change in higher probability nesting and core habitat, 1993 to 2017, by state and landowner

	Higher probability nesting habitat				Core habitat			
State/landowner	Loss (acres)	Gain (acres)	Net change (acres)	Net change (percent)	Loss (acres)	Gain (acres)	Net change (acres)	Net change (percent)
Washington								
Federal reserved	28,659	21,837	-6,823	-0.96	6,174	3,589	-2,585	-2.45
Federal nonreserved	2,272	3,645	1,373	3.59	123	123	0	0.00
Federal total	30,931	25,482	-5,449	-0.73	6,297	3,712	-2,585	-2.43
State	27,041	11,934	-15,107	-13.74	381	252	-129	-3.21
Other landowners	56,297	12,816	-43,481	-30.49	648	210	-437	-18.60
Total	114,269	50,232	-64,037	-6.40	7,326	4,175	-3,151	-2.80
Oregon								
Federal reserved	14,632	40,206	25,574	10.30	1,212	1,869	657	5.72
Federal nonreserved	2,814	13,225	10,412	37.37	67	321	254	32.33
Federal total	17,446	53,431	35,985	13.04	1,279	2,190	911	7.43
State	13,375	37,927	24,552	43.42	236	1,066	830	165.10
Other landowners	70,692	56,621	-14,072	-10.15	1,490	417	-1,072	-65.70
Total	101,513	147,979	46,466	9.86	3,004	3,673	669	4.64
California								
Federal reserved	461	284	-177	-1.55	46	40	-6	-0.17
Federal nonreserved	4	16	12	2.50	0	0	0	0.00
Federal total	465	299	-165	-1.40	46	40	-6	-0.17
State	422	370	-52	-0.25	54	36	-17	-0.19
Other landowners	3,458	399	-3,059	-31.51	18	1	-17	-69.09
Total	4,344	1,068	-3,276	-7.83	118	77	-41	-0.31
Plan area total								
Federal reserved	43,752	62,327	18,574	1.92	7,433	5,498	-1,935	-1.61
Federal nonreserved	5,089	16,886	11,796	17.72	190	444	254	15.35
Federal total	48,841	79,212	30,371	2.93	7,623	5,942	-1,681	-1.38
State	40,838	50,232	9,394	5.03	671	1,355	684	4.93
Other landowners	130,447	69,835	-60,611	-20.83	2,155	628	-1,527	-38.08
Total	220,126	199,280	-20,847	-1.38	10,448	7,925	-2,524	-1.80

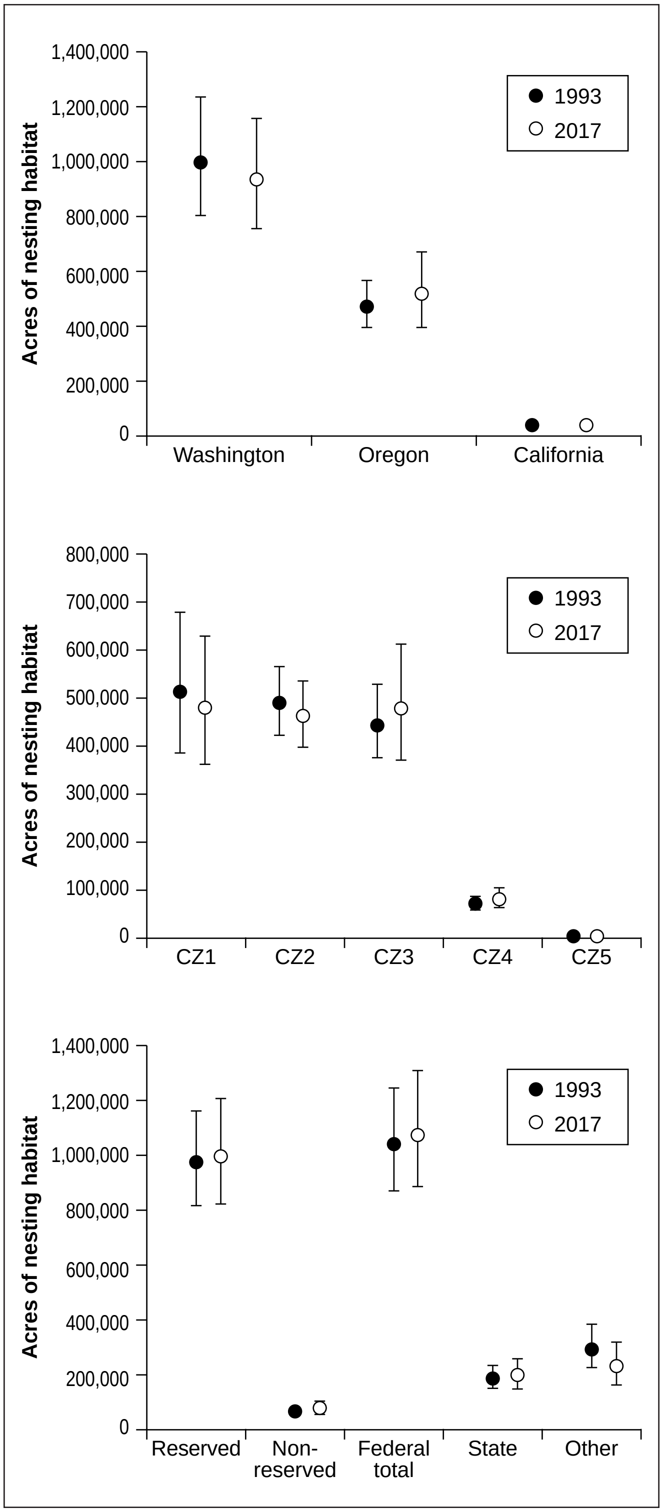

Figure 16—Mean acres of higher probability nesting habitat (with 95 percent confidence intervals) in 1993 and 2017 by state, conservation zone (CZ), and landowner.

from 1993 to 2017 on federal and state lands, but declined (-60,611 acres, $P < 0.05$) on other lands in the NWFP area (table 9, fig. 16). Most increases in higher probability nesting habitat were due to increases in scatter, primarily in Oregon (table 10). Federal reserved and state lands in Washington and California, and other lands in all three states showed net losses in core habitat (tables 9 and 10).

Of losses for which we were able to attribute a cause (74 percent of all losses), we attributed the vast majority (96 percent) to timber harvest (155,836 acres) (table 11). Other disturbances, which includes landslides or blowdowns, accounted for 2 percent of attributable losses, or 2,852 acres. NWFP-wide, wildfire accounted for 3,338 acres of habitat loss, most of which occurred in Washington (table 11), with only 820 acres lost to insect damage. Losses in core habitat were similarly distributed among these disturbance categories. Losses in core habitat were mostly attributed to timber harvest (2,618 acres), followed by wildfire (549 acres) and other disturbances (412 acres). However, it is important to note that most losses (66 percent) in core habitat could not be attributed to a cause (6,862 acres) (table 11).

Summary of Nesting Habitat in Washington

In Washington, we estimated there were 1,000,018 acres of higher probability nesting habitat in 1993 (table 7, fig. 16). Most of this habitat was on federal reserved lands (709,216 acres) (table 7), with smaller amounts on other (142,627 acres), state (109,907 acres), and federal nonreserved lands (38,268 acres). We classified 112,605 acres (11 percent) as core habitat in 1993; most (70 percent) higher probability nesting habitat was scatter (704,459 acres) (table 8). Between 1993 and 2017, Washington experienced net losses in nesting (-64,037 acres) and core habitat (-3,151 acres) (table 9, figs. 16, 17). The only notable net habitat gain in Washington was for scatter on federal lands (table 10). The largest net losses were on state (-15,107 acres) and other nonfederal lands (-43,481 acres) (table 9, figs. 18, 19, 20). Among gross losses with attributable causes (71 percent), most were attributed to timber harvest and were on state and other lands (table 11); however, 29 percent of the losses could not be assigned to

Table 10—Net changes in acres of higher probability nesting habitat and core, edge, and scatter between 1993 and 2017 by state and landowner

State/landowner	Higher probability nesting habitat	Core	Edge	Scatter
Washington				
Federal reserved	-6,824	-2,585	-3,683	-556
Federal nonreserved	1,373	0	37	1,336
Federal total	-5,451	-2,585	-3,646	780
State	-15,107	-128	-762	-14,217
Other landowners	-43,480	-437	-1,725	-41,318
Total	-64,038	-3,150	-6,133	-54,755
Oregon				
Federal reserved	25,573	656	2,251	22,665
Federal nonreserved	10,413	254	848	9,310
Federal total	35,986	910	3,099	31,975
State	24,553	830	1,857	21,866
Other landowners	-14,073	-1,072	-3,651	-9,347
Total	46,466	668	1,305	44,494
California				
Federal reserved	-177	-6	2	-174
Federal nonreserved	12	0	-6	18
Federal total	-165	-6	-4	-156
State	-53	-18	31	-66
Other landowners	-3,058	-16	-122	-2,920
Total	-3,276	-40	-95	-3,142
Plan area total				
Federal reserved	18,572	-1,935	-1,430	21,935
Federal nonreserved	11,798	254	879	10,664
Federal total	30,370	-1,681	-551	32,599
State	9,403	684	1,126	7,583
Other landowners	-60,621	-1,525	-5,498	-53,585
Total	-20,848	-2,522	-4,923	-13,403

Note: Color gradient indicates the percentile rank among all values in the analysis area and is bounded by the maximum (green) and minimum (red).

Table 11—Attribution of gross loss (acres) of higher probability nesting and core habitat by state and landowner using 1993–2017 bookend (cumulative) Landscape Change Monitoring System disturbance data

	Higher probability nesting habitat					Core habitat				
State/landowner	Timber harvest	Wildfire	Insect damage	Other	Unattributable loss	Timber harvest	Wildfire	Insect damage	Other	Unattributable loss
Washington										
Federal reserved	2,417	2,895	113	2,787	20,447	339	537	2	407	4,889
Federal nonreserved	687	27	1	1	1,556	7	0	0	0	115
Federal total	3,103	2,923	114	2,788	22,003	346	537	2	407	5,005
State	21,383	2	137	2	5,518	180	0	0	0	201
Other landowners	49,857	92	415	17	5,916	525	0	3	2	117
Total	74,343	3,017	666	2,807	33,436	1,051	537	6	409	5,323
Oregon										
Federal reserved	1,774	38	2	30	12,788	111	0	0	3	1,098
Federal nonreserved	1,052	0	0	1	1,760	13	0	0	0	54
Federal total	2,826	38	2	31	14,548	124	0	0	3	1,152
State	10,331		10		3,034	121	0	0	0	115
Other landowners	65,492	39	137	0	5,023	1,310	0	2	0	178
Total	78,650	77	149	31	22,606	1,554	0	2	3	1,445
California										
Federal reserved	14	238	1	14	193	1	12	0	0	34
Federal nonreserved	0	0	0	0	4	0	0	0	0	0
Federal total	14	238	1	14	197	1	12	0	0	34
State	147	1	0	0	274	5	0	0	0	49
Other landowners	2,683	5	3	0	767	6	0	0	0	11
Total	2,844	244	4	14	1,238	12	12	0	0	94
Plan area total										
Federal reserved	4,205	3,172	116	2,831	33,429	451	549	2	410	6,022
Federal nonreserved	1,739	28	2	2	3,319	20	0	0	0	170
Federal total	5,944	3,199	117	2,833	36,748	471	549	2	410	6,191
State	31,860	3	148	2	8,825	306	0	0	0	365
Other landowners	118,032	136	555	17	11,707	1,841	0	5	2	306
Total	155,836	3,338	820	2,852	57,280	2,618	549	8	412	6,862

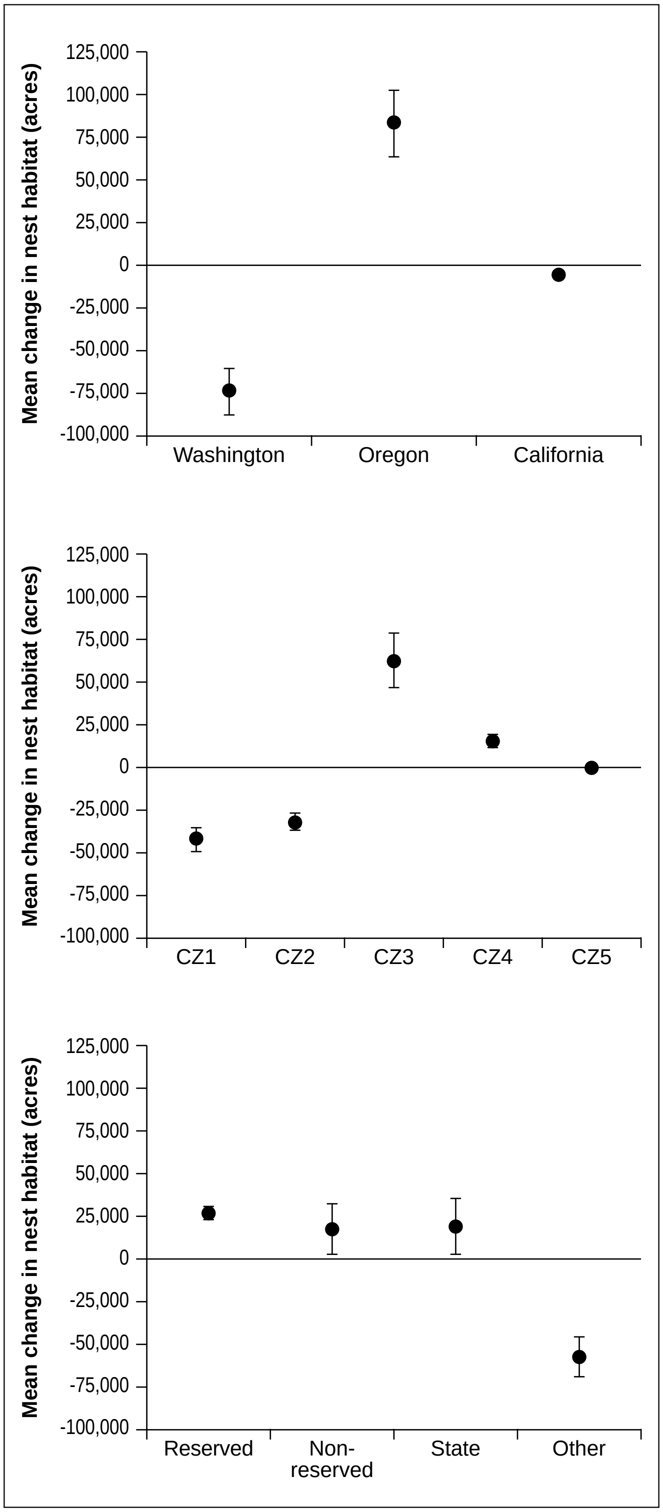

Figure 17—Change in acres of higher probability nesting habitat from 1993 to 2017, averaged among 25 replicated Maxent model runs by state, conservation zone, and landowner. Vertical bars denote 95 percent confidence intervals.

a disturbance agent. The largest net losses in core habitat occurred on federal reserved lands (-2,585 acres) tables 9 and 10); however, the greatest net percentages of loss occurred on nonfederal lands (table 9). Most gross losses in core habitat on federal reserves in Washington were attributed to other disturbances (407 acres) and wildfire (537 acres) (table 11), whereas the gross losses of higher probability nesting habitat and core habitat on nonfederal lands were attributed to timber harvest. The majority (73 percent) of core habitat losses could not be assigned to a disturbance agent.

Summary of Nesting Habitat in Oregon

Our models estimated that Oregon contained 471,220 acres of higher probability nesting habitat in 1993 (table 7, fig. 16). Approximately half of this habitat was on federal reserved lands (248,182 acres), as was most (80 percent) core habitat (11,476 acres) (table 8). The majority (86 percent) of higher probability nesting habitat was comprised of scatter, with only 3 percent core habitat. Our models indicated that small increases in higher probability nesting and core habitat occurred in Oregon between 1993 and 2017 (however, see “Sources of Uncertainty” below), with a statewide net change of 46,466 acres of higher probability nesting habitat and 669 acres of core habitat (table 9, figs. 16, 17). The largest net gains were on federal reserved (a 25,574-acre net change for higher probability nesting habitat and 657 acres for core habitat) and state lands (a 24,552-acre net change in higher probability nesting habitat and 830 acres for core habitat). However, almost all the gains in Oregon were due to increases in scatter (table 10).

Despite these net increases in higher probability nesting habitat in Oregon, we did document some losses of habitat (table 9) that are masked when considering only net change. We estimated that 101,513 acres of higher probability nesting habitat and 3,004 acres of core habitat were lost between 1993 and 2017. The overwhelming majority of habitat losses were attributed to timber harvest, primarily on other and state landownerships (table 11; figs. 18, 19, 20). Losses in core habitat were similarly attributed to timber harvest mostly; however, 48 percent of the losses in core habitat could not be assigned to a disturbance agent (table 11).

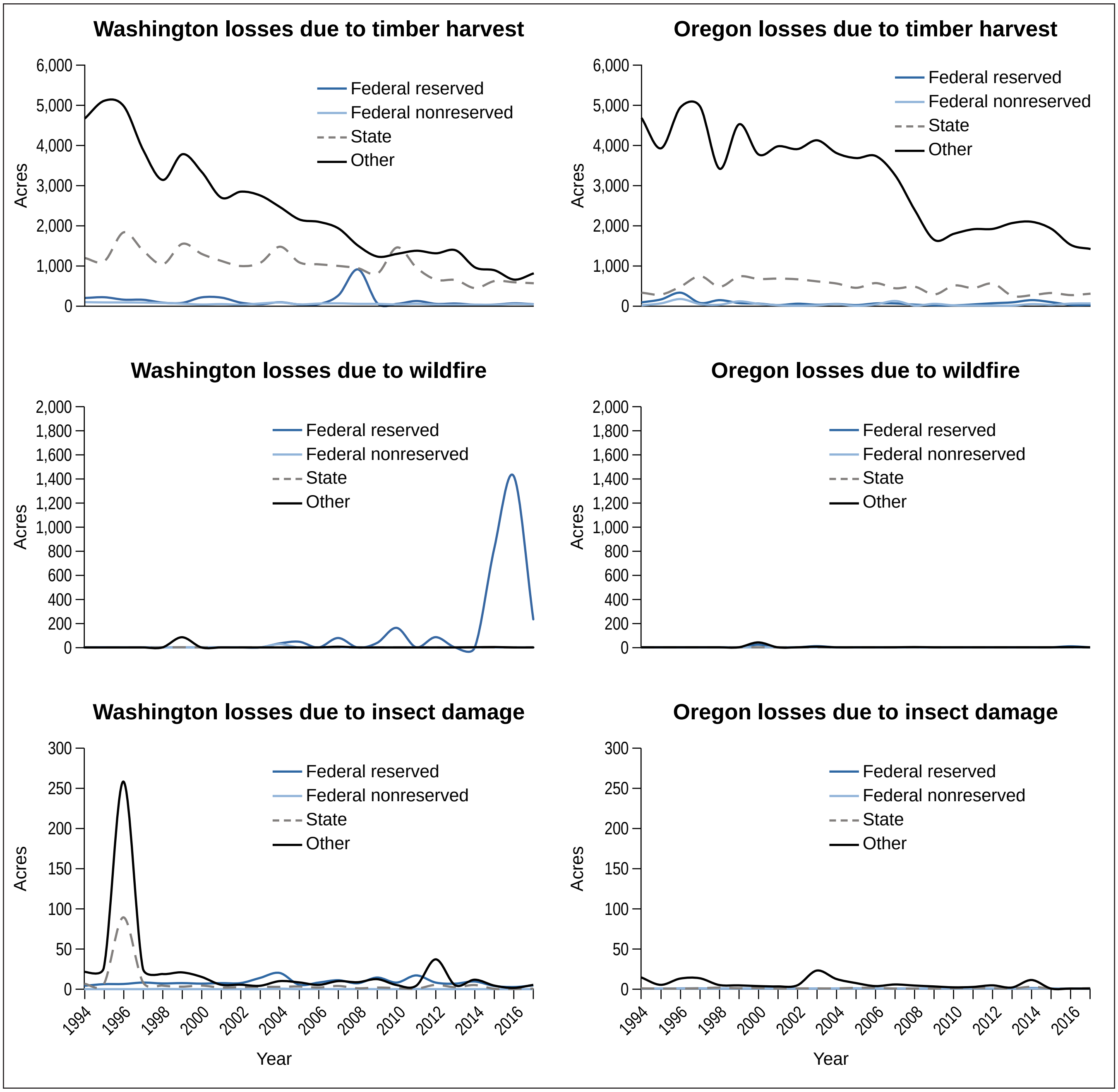

Figure 18—Losses of higher probability nesting habitat for each year from 1993 to 2017 attributed to timber harvest, wildfire, and insect damage by state and landowner.

Our models did not document large losses from the 2002 Biscuit Fire in Oregon because most of the area within the fire footprint was not classified as higher probability nesting habitat in 1993; therefore, these acres could not be counted as lost in our models. The lack of any training sites (nests) in the Klamath region may have contributed to few acres there being modeled as higher probability nesting habitat in this analysis. As noted earlier, the late summer-autumn 2017 Chetco Bar Fire was not included in our analysis, which included only disturbance up to summer 2017. Thus, in Oregon, we attributed only 77 acres of higher probability nesting habitat loss to wildfire and 0 acres of core habitat loss to wildfire (table 11).

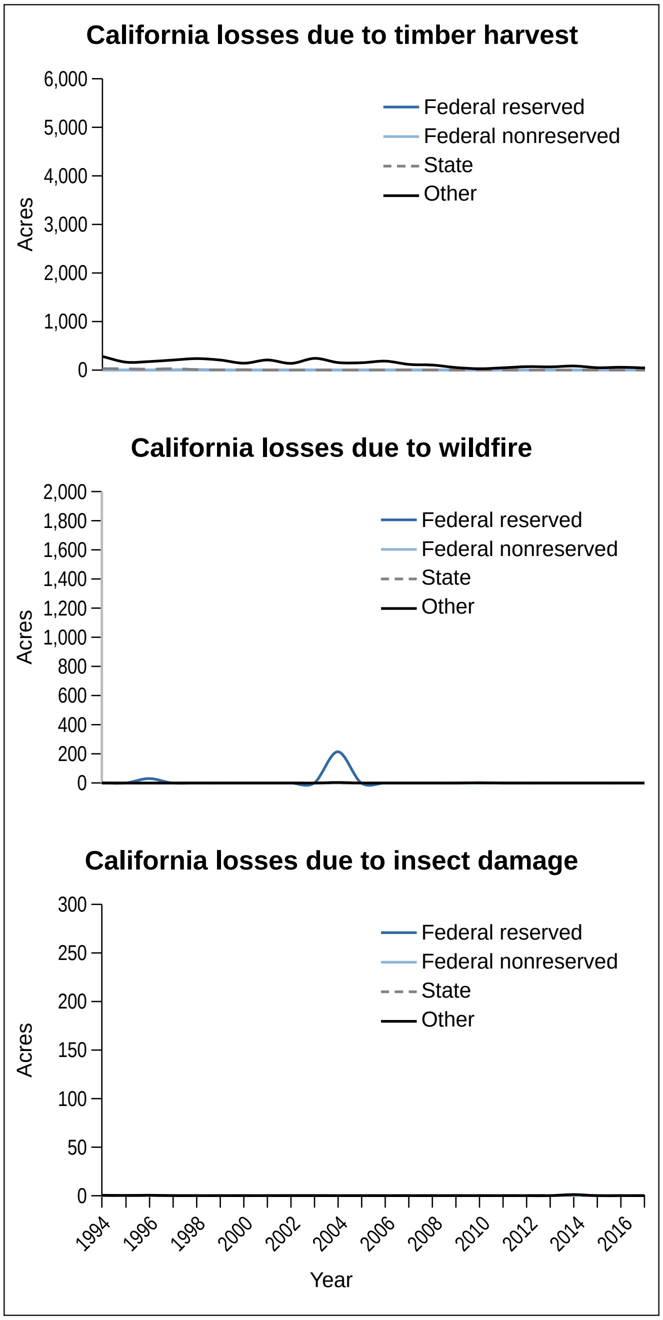

Figure 18—(continued)

Summary of Nesting Habitat in California

For California, we estimated there were 41,840 acres of higher probability nesting habitat in 1993 (fig. 14). Approximately half of this habitat was on state lands (20,295 acres) (table 7, fig. 12). Compared with Washington and Oregon where only a fraction of habitat was modeled as core, a larger proportion of California higher probability nesting habitat was modeled as core (30 percent) (table 8). This represents unharvested older forests within national and state parks and reserves, such as Del Norte, Jedediah Smith, Prairie Creek, and Humboldt Redwoods State Parks; Redwood National Park; and the Bureau of Land Management's Headwaters Forest Reserve.

We estimated that California contained 38,564 acres of higher probability nesting habitat (table 7) in 2017, which represents a net loss of 7.83 percent between 1993 and 2017 (table 9). The greatest net losses in higher probability nesting habitat occurred on other lands (-3,059 acres) (table 9; figs. 16, 17). The greatest net losses in core habitat occurred on state and other lands, both of which lost 17 acres (table 9). Most of the attributable losses in California were due to timber harvest (2,844 acres) (table 11; figs. 18, 19, 20) with negligible losses from all other disturbance categories. However, like Oregon and Washington, about one-third of all losses could not be attributed to a disturbance agent.

Summary of Nesting Habitat by Murrelet Conservation Zone

We separately estimated the amount of higher probability nesting habitat in each murrelet conservation zone (tables 12 through 16, fig. 16). Changes in higher probability nesting habitat were significant in each conservation zone (matched-pair t-tests, $P < 0.05$). The greatest losses occurred in conservation zones 1 and 2 in Washington, with net changes of -35,851 acres and -28,186 acres, respectively (table 14, fig. 17). conservation zones 3 and 4 include the northern and central Oregon coast (conservation zone 3) and the southern Oregon coast and northern California coast (conservation zone 4). Both zones showed small increases in higher probability nesting habitat that was almost all scatter totaling a combined 43,221 acres (tables 14 and 15). As discussed above in the results for Oregon, there were some habitat losses modeled in conservation zones 3 and 4 (table 14), but these losses are masked when considering only net change. In California, conservation zone 5 contained a very small amount of higher probability nesting habitat (2,107 acres in 1993) (table 12) and almost all of it was modeled as scatter (table 13). Conservation zone 5 experienced a 1-percent net

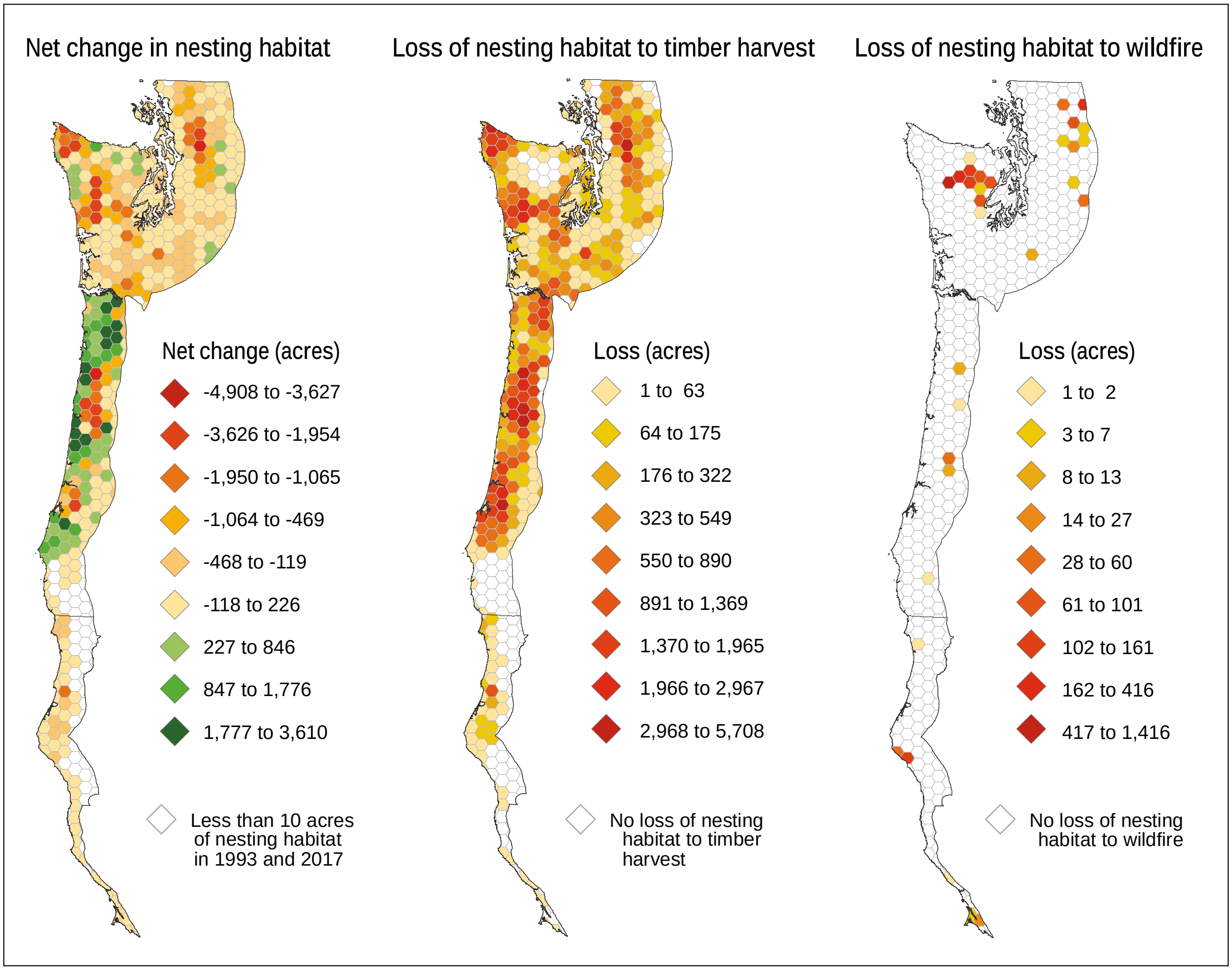

Figure 19—Net change in acres of higher probability nesting habitat and losses due to timber harvest and wildfire, 1993 to 2017. The range of possible values are classified using the Jenks optimization method, or natural breaks, which determines the best arrangement of values into different classes by minimizing each class's average deviation from the mean, while maximizing each class's deviation from the means of the other groups, therefore reducing the variance within classes and maximizing the variance between classes.

decrease in habitat from 1993 to 2017 (table 14). For all other conservation zones, most attributable habitat loss (88 to 100 percent) was due to timber harvest (table 16).

Effects of Human Disturbance

The human footprint model that we used from Theobald (2013) classified all lands within our analysis area between 0 and 1, with 0 indicating low human influence (e.g., wilderness areas) and 1 indicating extremely high human influence (e.g., interstate highways, urban areas). Bearing in mind that we estimated human footprint only for habitat-capable lands, we found that higher probability nesting habitat had a lower human footprint rank on average in Washington and Oregon, but not in California (table 17). California differed because a large proportion of higher probability nesting habitat occurred on state and national park lands heavily used for recreation. In all states, there was a trend for federal lands to have a lower footprint than state and other lands. There was also a trend for core habitat to have a lower footprint than scatter. One exception was that state lands in Oregon had higher footprint for core habitat (table 17).

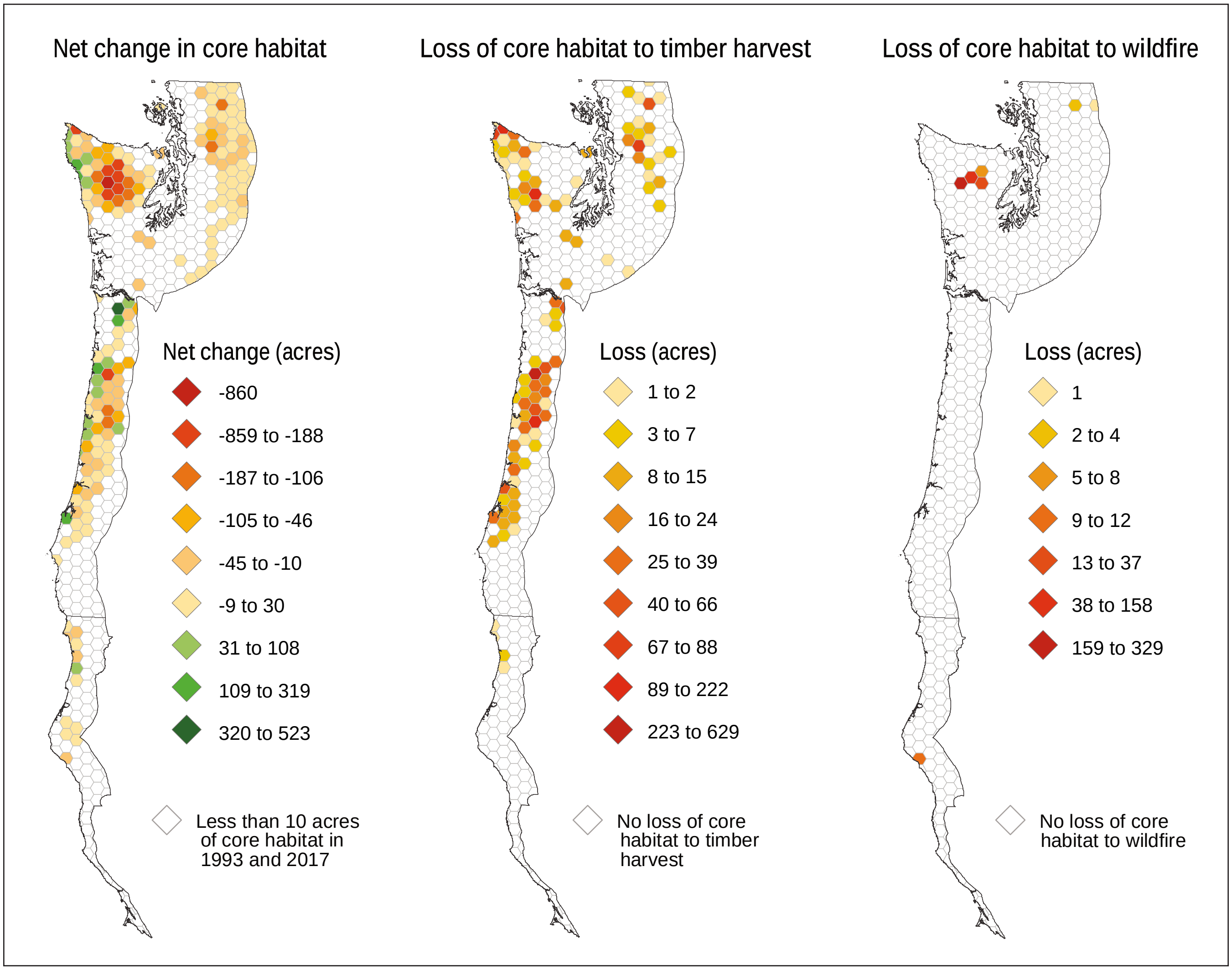

Figure 20—Net change in acres of higher probability core habitat, as well as losses due to timber harvest and wildfire, 1993 to 2017. The range of possible values are classified using the Jenks optimization method.

Relationship Between Nesting Habitat and Populations

We did not see a relationship between the amount of higher probability nesting habitat and at-sea abundance among states or conservation zones (fig. 21). However, we did see a relationship between change in amount of higher probability nesting habitat from 1993 to 2017 and murrelet at-sea abundance trend at the state and conservation zone levels (fig. 22), as indicated by confidence intervals that did not overlap zero. In Washington, loss of higher probability nesting habitat corresponded with declines in murrelet abundance, and in Oregon, a small increase in higher probability nesting habitat corresponded with a slight increase in murrelet at-sea abundance. Results for California did not fit this pattern, however. For California we saw an increase in murrelet abundance, but a decrease in higher probability nesting habitat. When comparing habitat and populations by conservation zone, we observed that losses of higher probability nesting habitat in conservation zone 1 corresponded with decreases in murrelet abundance. Increases in habitat in conservation zone 4 corresponded with increases in murrelet abundance. Relationships in conservation zones 2, 3, and 5 were indeterminant because confidence intervals overlapped zero.

Table 12—Acres of lower, moderate, and higher probability nesting habitat by conservation zone and landowner for the baseline period (1993) and final year of analysis (2017)

	1993			2017		
Conservation zone/ landowner	**Lower probability**	**Moderate probability**	**Higher probability**	**Lower probability**	**Moderate probability**	**Higher probability**
Conservation zone 1						
Federal reserved	1,160,322	898,056	332,716	1,136,983	921,404	332,707
Federal nonreserved	254,749	91,248	30,494	234,942	109,591	31,958
Federal total	1,415,071	989,304	363,210	1,371,925	1,030,995	364,665
State	823,964	235,272	64,106	874,261	198,537	50,544
Other landowners	3,108,200	407,075	85,329	3,261,085	277,935	61,584
Total	5,347,235	1,631,651	512,645	5,507,271	1,507,467	476,793
Conservation zone 2						
Federal reserved	167,404	118,775	376,500	150,170	142,824	369,685
Federal nonreserved	52,116	9,838	7,774	40,459	21,586	7,683
Federal total	219,520	128,613	384,274	190,629	164,410	377,368
State	423,030	54,750	45,801	403,330	75,995	44,256
Other landowners	1,887,738	156,759	57,297	1,970,178	94,054	37,562
Total	2,530,288	340,122	487,372	2,564,137	334,459	459,186
Conservation zone 3						
Federal reserved	613,841	150,677	233,949	529,773	214,391	254,302
Federal nonreserved	189,130	24,761	26,533	156,238	48,372	35,814
Federal total	802,971	175,438	260,482	686,011	262,763	290,116
State	528,023	101,038	56,364	441,894	163,296	80,235
Other landowners	2,319,539	189,962	123,006	2,340,464	187,832	104,210
Total	3,650,533	466,438	439,852	3,468,369	613,891	474,561
Conservation zone 4						
Federal reserved	1,697,535	25,309	25,077	1,683,252	34,503	30,167
Federal nonreserved	431,114	3,087	1,787	426,068	7,000	2,920
Federal total	2,128,649	28,396	26,864	2,109,320	41,503	33,087
State	112,972	5,718	19,957	112,991	5,068	20,588
Other landowners	2,370,031	44,425	24,279	2,357,611	55,188	25,936
Total	4,611,652	78,539	71,100	4,579,922	101,759	79,611
Conservation zone 5						
Federal reserved	25,146	1,841	532	25,840	1,195	484
Federal nonreserved	265	16	1	239	32	11
Federal total	25,411	1,857	533	26,079	1,227	495
State	61,144	1,807	512	61,092	1,860	511
Other landowners	442,026	7,073	1,062	442,980	6,109	1,071
Total	528,581	10,737	2,107	530,151	9,196	2,077

Table 13—Distribution of higher probability core, edge, and scatter habitat (acres) by murrelet conservation zone and landowner for the baseline period (1993) and final year of analysis (2017)

	1993			2017		
Conservation zone/landowner	**Core**	**Edge**	**Scatter**	**Core**	**Edge**	**Scatter**
Conservation zone 1						
Federal reserved	15,503	43,004	274,209	15,031	42,016	275,661
Federal nonreserved	702	3,024	26,768	687	3,069	28,202
Federal total	16,205	46,028	300,977	15,718	45,085	303,863
State	772	3,167	60,167	620	2,357	47,568
Other landowners	603	2,101	82,625	278	946	60,360
Total	17,580	51,296	443,769	16,616	48,388	411,791
Conservation zone 2						
Federal reserved	89,869	119,456	167,175	87,756	116,761	165,168
Federal nonreserved	159	626	6,989	174	618	6,891
Federal total	90,028	120,082	174,164	87,930	117,379	172,059
State	3,249	8,371	34,181	3,272	8,420	32,564
Other landowners	1,749	3,204	52,344	1,637	2,634	33,291
Total	95,026	131,657	260,689	92,839	128,433	237,914
Conservation zone 3						
Federal reserved	11,256	38,220	184,473	11,863	40,174	202,266
Federal nonreserved	780	3,087	22,666	1,028	3,894	30,891
Federal total	12,036	41,307	207,139	12,891	44,068	233,157
State	484	2,837	53,043	1,244	4,559	74,433
Other landowners	1,555	6,404	115,047	461	2,735	101,016
Total	14,075	50,548	375,229	14,596	51,362	408,606
Conservation zone 4						
Federal reserved	3,920	4,038	17,119	3,963	4,337	21,867
Federal nonreserved	15	76	1,696	20	111	2,789
Federal total	3,935	4,114	18,815	3,983	4,448	24,656
State	9,375	5,176	5,406	9,428	5,342	5,818
Other landowners	101	650	23,528	107	546	25,283
Total	13,411	9,940	47,749	13,518	10,336	55,757
Conservation zone 5						
Federal reserved	0	0	532	0	0	483
Federal nonreserved	0	0	1	0	0	11
Federal total	0	0	533	0	0	494
State	0	6	506	0	6	504
Other landowners	0	0	1,062	0	0	1,071
Total	0	6	2,101	0	6	2,069

Table 14—Acreage loss, gain, and net change in higher probability nesting and core habitat from 1993 to 2017 by murrelet conservation zone and landowner

	Higher probability nesting habitat				Core habitat			
Conservation zone/landowner	Loss (acres)	Gain (acres)	Net changes (acres)	Net changes (percent)	Loss (acres)	Gain (acres)	Net changes (acres)	Net changes (percent)
Conservation zone 1								
Federal reserved	13,493	13,485	-8	0.00	983	511	-472	-3.05
Federal nonreserved	1,324	2,788	1,465	4.80	69	54	-14	-2.03
Federal total	14,817	16,273	1,456	0.40	1,052	565	-487	-3.00
State	20,192	6,631	-13,562	-21.16	192	40	-152	-19.71
Other landowners	29,090	5,345	-23,745	-27.83	346	21	-325	-53.97
Total	64,099	28,248	-35,851	-6.99	1,590	626	-964	-5.488
Conservation zone 2								
Federal reserved	15,166	8,352	-6,814	-1.81	5,191	3,078	-2,113	-2.35
Federal nonreserved	948	857	-91	-1.18	54	68	15	9.21
Federal total	16,114	9,209	-6,906	-1.80	5,244	3,146	-2,098	-2.33
State	6,848	5,304	-1,545	-3.37	190	213	23	0.71
Other landowners	27,207	7,472	-19,735	-34.44	302	190	-112	-6.41
Total	50,170	21,984	-28,186	-5.78	5,736	3,549	-2,187	-2.30
Conservation zone 3								
Federal reserved	13,656	34,011	20,355	8.70	1,185	1,792	607	5.39
Federal nonreserved	2,548	11,828	9,280	34.98	66	314	249	31.89
Federal total	16,204	45,839	29,635	11.38	1,251	2,106	856	7.11
State	13,374	37,245	23,871	42.35	236	995	759	156.87
Other landowners	63,750	44,954	-18,796	-15.28	1,439	344	-1,095	-70.39
Total	93,327	128,037	34,710	7.89	2,925	3,445	520	3.70
Conservation zone 4								
Federal reserved	1,352	6,443	5,091	20.30	74	117	43	1.10
Federal nonreserved	270	1,403	1,133	63.41	2	7	5	34.33
Federal total	1,622	7,846	6,224	23.17	75	124	48	1.23
State	401	1,032	631	3.16	54	107	53	0.57
Other landowners	10,334	11,990	1,656	6.82	68	74	6	5.49
Total	12,357	20,869	8,511	11.97	198	305	107	0.80
Conservation zone 5								
Federal reserved	84	36	-48	-9.11	0	0	0	0
Federal nonreserved	0	10	10	880.00	0	0	0	0
Federal total	84	45	-39	-7.26	0	0	0	0
State	22	21	-2	-0.30	0	0	0	0
Other landowners	66	75	9	0.84	0	0	0	0
Total	173	141	-31	-1.49	0	0	0	0

Table 15—Acreage net changes of total higher probability nesting habitat core, edge, and scatter components by murrelet conservation zone and landowner, 1993 to 2017

State/landowner	Higher probability nesting habitat	Core	Edge	Scatter
Conservation zone 1				
Federal reserved	-9	-472	-988	1,452
Federal nonreserved	1,464	-15	45	1,434
Federal total	1,455	-487	-943	2,886
State	-13,562	-152	-810	-12,599
Other landowners	-23,745	-325	-1,155	-22,265
Total	-35,852	-964	-2,908	-31,978
Conservation zone 2				
Federal reserved	-6,815	-2,113	-2,695	-2,007
Federal nonreserved	-91	15	-8	-98
Federal total	-6,906	-2,098	-2,703	-2,105
State	-1,545	23	49	-1,617
Other landowners	-19,735	-112	-570	-19,053
Total	-28,186	-2,187	-3,224	-22,775
Conservation zone 3				
Federal reserved	20,353	607	1,954	17,793
Federal nonreserved	9,281	248	807	8,225
Federal total	29,634	855	2,761	26,018
State	23,871	760	1,722	21,390
Other landowners	-18,796	-1,094	-3,669	-14,031
Total	34,709	521	814	33,377
Conservation zone 4				
Federal reserved	5,090	43	299	4,748
Federal nonreserved	1,133	5	35	1,093
Federal total	6,223	48	334	5,841
State	631	53	166	412
Other landowners	1,657	6	-104	1,755
Total	8,511	107	396	8,008
Conservation zone 5				
Federal reserved	-48	0	0	-49
Federal nonreserved	10	0	0	10
Federal total	-38	0	0	-39
State	-1	0	0	-2
Other landowners	9	0	0	9
Total	-30	0	0	-32

Note: Color gradient indicates the percentile rank among all values in the analysis area and is bounded by the maximum (green) and minimum (red).

Table 16—Attribution of gross loss (acres) of higher probability nesting and core habitat by state and landowner using 1993–2017 bookend (cumulative) Landscape Change Monitoring System disturbance data (continued)

	Higher probability nesting habitat					Core habitat				
Conservation zone/ landowner	**Timber harvest**	**Wildfire**	**Insect damage**	**Other**	**Unattributable loss**	**Timber harvest**	**Wildfire**	**Insect damage**	**Other**	**Unattributable loss**
Conservation zone 1										
Federal reserved	1,234	974	81	953	10,251	84	13	1	55	830
Federal nonreserved	484	27	0	0	812	6	0	0	0	63
Federal total	1,718	1,001	81	953	11,063	89	13	1	55	893
State	16,547	2	24	1	3,618	136	0	0	0	55
Other landowners	24,764	92	91	2	4,141	303	0	2	0	41
Total	43,029	1,095	197	956	18,822	529	13	3	55	990
Conservation zone 2										
Federal reserved	1,182	1,921	32	1,835	10,196	255	524	1	352	4,059
Federal nonreserved	203	0	1	0	744	1	0	0	0	52
Federal total	1,385	1,921	33	1,835	10,940	257	524	1	352	4,111
State	4,836	0	113	1	1,900	44	0	0	0	146
Other landowners	25,093	0	323	15	1,775	222	0	2	2	76
Total	31,314	1,921	469	1,851	14,615	522	524	3	354	4,333
Conservation zone 3										
Federal reserved	1,430	37	1	30	12,159	105	0	0	3	1,077
Federal nonreserved	886	0	0	1	1,660	13	0	0	0	53
Federal total	2,316	37	1	31	13,819	118	0	0	3	1,130
State	10,331	0	10	0	3,033	121	0	0	0	115
Other landowners	58,922	39	124	0	4,664	1,261	0	2	0	176
Total	71,569	76	136	31	21,516	1,499	0	2	3	1,421

Table 16—Attribution of gross loss (acres) of higher probability nesting and core habitat by state and landowner using 1993–2017 bookend (cumulative) Landscape Change Monitoring System disturbance data (continued)

	Higher probability nesting habitat					Core habitat				
Conservation zone/ landowner	**Timber harvest**	**Wildfire**	**Insect damage**	**Other**	**Unattributable loss**	**Timber harvest**	**Wildfire**	**Insect damage**	**Other**	**Unattributable loss**
Conservation zone 4										
Federal reserved	354	210	2	8	779	6	12	0	0	55
Federal nonreserved	166	0	0	0	103	0	0	0	0	2
Federal total	520	210	2	8	882	7	12	0	0	57
State	145	0	0	0	256	5	0	0	0	49
Other landowners	9,232	5	16	0	1,082	56	0	0	0	13
Total	9,897	215	17	8	2,220	68	12	0	0	118
Conservation zone 5										
Federal reserved	4	29	0	6	44	0	0	0	0	0
Federal nonreserved	0	0	0	0	0	0	0	0	0	0
Federal total	4	29	0	6	44	0	0	0	0	0
State	2	1	0	0	19	0	0	0	0	0
Other landowners	22	0	0	0	45	0	0	0	0	0
Total	28	30	1	6	108	0	0	0	0	0

Table 17—Mean human footprint rank of higher probability nesting habitat in 2017 by state and landowner

State/landowner	Nonnesting habitat	Higher probability nesting habitat	Core[a]	Edge[a]	Scatter
Washington					
Federal reserved	0.17	0.14	0.11	0.12	0.15
Federal nonreserved	0.28	0.26	0.22	0.24	0.27
State	0.30	0.23	0.16	0.17	0.25
Other landowners	0.38	0.37	0.19	0.26	0.38
Washington average	0.28	0.18	0.11	0.13	0.20
Oregon					
Federal reserved	0.19	0.22	0.20	0.21	0.23
Federal nonreserved	0.23	0.25	0.21	0.23	0.25
State	0.29	0.27	0.28	0.28	0.27
Other landowners	0.32	0.34	0.33	0.33	0.34
Oregon average	0.26	0.26	0.21	0.22	0.27
California					
Federal reserved	0.23	0.29	0.27	0.30	0.29
Federal nonreserved	0.26	0.18	0.14	0.18	0.19
State	0.32	0.46	0.41	0.50	0.51
Other landowners	0.27	0.43	0.41	0.48	0.42
California average	0.27	0.40	0.37	0.43	0.41

[a] Some categories have extremely small acreages and thus estimates of human footprint reflect footprint in an extremely small area. For example, we estimated that federal nonreserved lands in California included 8 acres of core habitat (see table 8). The estimated footprint from such small areas may not be meaningful when compared to other categories with many more acres, such as California state lands, which included 9,357 acres of core habitat (table 8).

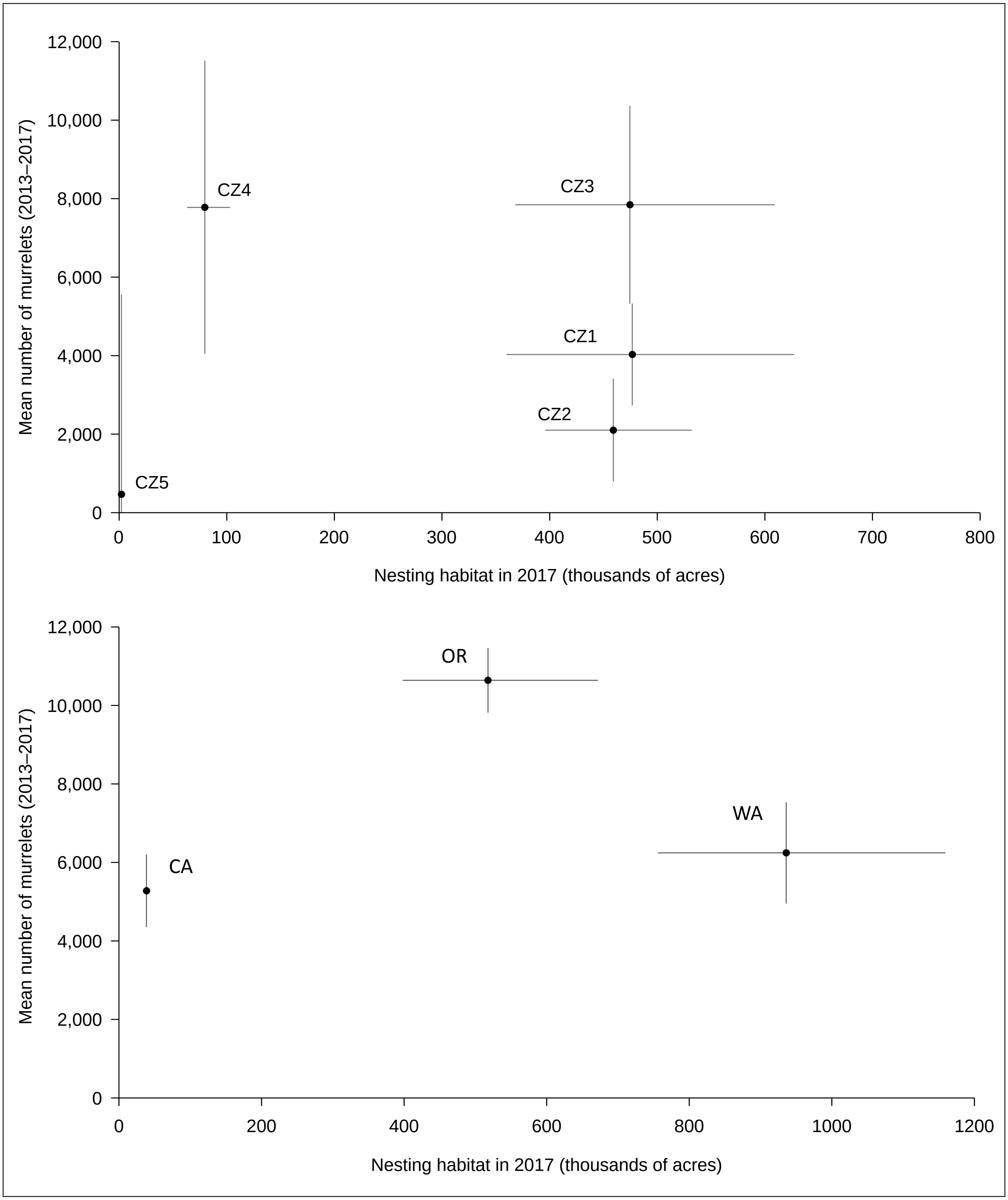

Figure 21—Relationship between murrelet population size, 2013–2017 (source: McIver et al. 2021), and acres of higher probability nesting habitat in 2017 for each state and conservation zone (CZ).

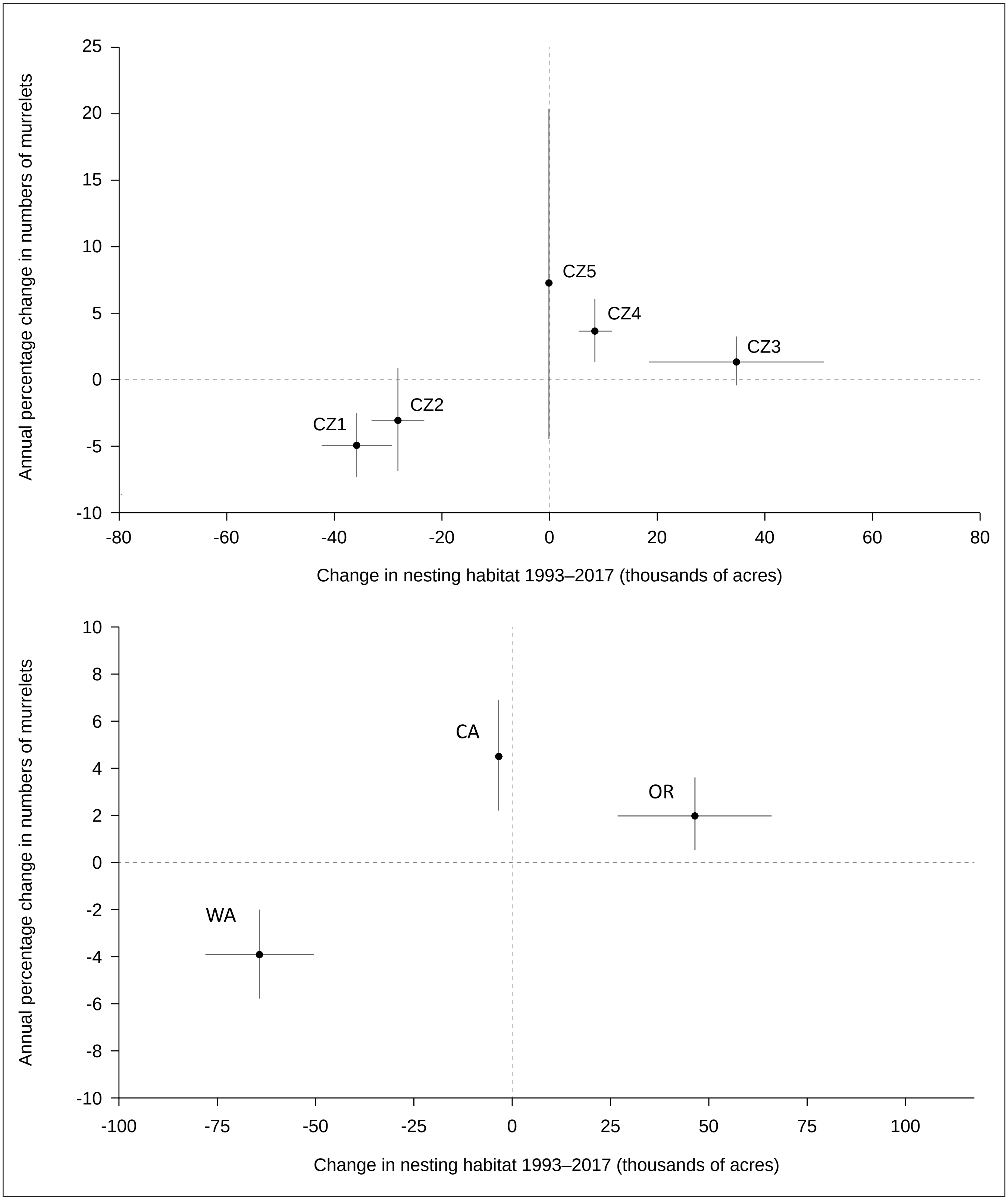

Figure 22—Relationship between annual population trend, 2000–2017 (McIver et al. 2021) and change in higher probability nesting habitat, 1993–2017 by state and conservation zone (CZ).

Discussion

We estimated that among 21 million habitat-capable acres in Washington, Oregon, and California, 1.49 million acres were higher probability nesting habitat for the marbled murrelet in 2017. This represents a net decrease of 20,847 acres of higher probability nesting habitat since the start of the NWFP. We estimated that core habitat declined by 1.8 percent throughout the NWFP area. For federal lands, we estimated habitat increased by 2.93 percent throughout the NWFP area, and most of these gains were on federal reserve lands, which had a net increase of 18,574 acres, primarily due to net increases in Oregon. Unfortunately, this was not true for core habitat. Federal lands and federal reserved lands experienced net decreases in core habitat of 1.38 and 1.61 percent, respectively (table 9).

The original goal of the NWFP was to increase habitat for the marbled murrelet, and our results indicate this is not occurring for the highest quality habitat. We saw increases mostly in edge and scatter habitat, and research indicates that fragmented and edge habitats increase the risk of nest failure in this species (Malt and Lank 2007, 2009; Nelson and Hamer 1995; Raphael et al. 2002). In 2017, we estimated that 75 percent of the higher probability nesting habitat in the NWFP area was scatter, leaving only 25 percent in larger, contiguous patches of core habitat that occurred primarily in Washington.

Similar to Raphael et al. (2016), our models indicate that higher probability nesting habitat occurred on all lands in the NWFP area; thus, all lands play a role in the conservation of murrelet habitat. The greatest proportion (86 percent) of core habitat in the NWFP area currently occurs in reserve land use allocations on federal lands. We estimated that there were 118,613 acres of core habitat on federal reserves as of 2017, a net decrease of 1,935 acres since 1993. The NWFP system of reserve allocations was established to provide older, mature forest conditions for species such as the murrelet. However, we documented declines in core habitat on federal reserved lands that were equally attributed to timber harvest, wildfire, and other natural disturbances.

Nonfederal landowners (state and other) accounted for 29 percent of the higher probability nesting habitat in the NWFP area. Net losses in higher probability nesting habitat on these nonfederal lands in Washington and California were high between 1993 and 2017. We also estimated losses on other lands in Oregon. For state lands in Oregon, modeled gains exceeded the losses, resulting in small net gains (however, see “Sources of Uncertainty” below), primarily of scatter habitat. At the NWFP area-wide scale, as shown in table 10 and fig. 17, net gains in higher probability nesting habitat were observed for federal and state lands, but not for other landowners, where we observed a net loss. We attributed 99 percent of all higher probability nesting habitat losses on other lands to timber harvest. For core habitat, the net losses on nonfederal lands were higher when considering the percentage of habitat loss, but lower in terms of acreage, which can partially be attributed to the fact that state and other lands account for extremely small amounts of core habitat. For example, Oregon manages 694,985 habitat-capable acres, of which only 1,333 acres were modeled as core habitat in 2017. While this represents a gain relative to 1993, it accounts for only 830 acres of core habitat gained because many habitat-capable state lands in Oregon did not meet the criteria for classification as core habitat.

Nesting Habitat and Population Trend Relationships

We found little evidence of a correlation between the amount of higher probability nesting habitat and core habitat and at-sea abundance of murrelets at the scale of states and conservation zones. Previous studies have found correlations between murrelet densities at-sea and the amount of nesting habitat (Lorenz et al. 2016; Raphael et al. 2011, 2015, 2016). We did observe a positive relationship between the change in amount of higher probability nesting habitat and at-sea abundance. At-sea abundance increased along with habitat in Oregon and California and decreased in Washington. The absence of a strong correlation between at-sea abundance of murrelets and amount of habitat may be due to other factors that can influence murrelet densities at sea, such as movements of murrelets between conservation zones in response to ocean conditions and prey availability (see McIver et al. 2021).

Sources of Uncertainty

As with any large-scale habitat modeling effort, our analysis has uncertainties. For example, there is underlying inaccuracy in the GNN covariate data used in the models, which is normal for models created from satellite imagery at such large spatial scales. Accuracy assessments quantify some of this uncertainty, but in this analysis, we reduced the effect of covariate inaccuracy by selecting only GNN covariates with relatively high accuracy statistics. This differs from previous reports (Raphael et al. 2011, 2016) in which covariates were selected that described forest attributes that were important for murrelets. While we started with the same list of covariates for this analysis, we eliminated covariates that did not meet a certain minimum threshold of accuracy. There are strengths and weaknesses to either approach. However, we feel it is an improvement that the covariates we used in our current analysis have, on average, higher accuracy statistics than those used in previous reports.

For murrelets, there were additional GNN data shortcomings that affected our analysis. First, platform size and abundance are two of the best indicators of a forested area's suitability for murrelet nesting (Hamer and Nelson 1995; Hamer et al., in press) but are not modeled by the GNN process. In this report we used tree size as a proxy for platforms because tree size is correlated with platform abundance (Raphael et al. 2011), but this correlation is not perfect, and thus some stands that were classified as higher probability nesting habitat because they contain large trees may have lacked platforms needed for murrelet nesting. Additionally, some increases in murrelet nesting habitat that we reported may be due to increases in average tree diameter in a stand following thinning (i.e., when small trees are removed during thinning, average tree diameter increases, even when there has been no growth of the remaining trees). Such increases likely do not reflect increases in the availability of platforms in these stands. It is also important to consider that it may take >200 years for most tree species to develop and grow platforms. While we used the best data available to us, small changes in tree diameter or stand attributes that caused our models to show an increase in higher probability nesting habitat from 1993 to 2017 do not necessarily mean that nesting platforms were created or that habitat probability increased.

Our modeling approach also introduces some uncertainty. As noted in our methods, the Maxent model procedure has inherent variability due to stochastic processes built into the modeling software. Every model run produces a slightly different distribution of Maxent scores, partly because of randomly selected background points used to compare nest sites and available sites and partly due to stochastic elements of the machine learning algorithm. By running 25 replicated models, we were able to estimate variability due to these stochastic elements. An example of this variability is displayed in figure 16, which shows the 95 percent confidence intervals computed from the variance among the 25 model runs. Interpretation of all our acreage estimates, which are based on the averages of 25 Maxent model runs, should take into account the variability shown by those confidence intervals.

Another source of uncertainty is the misclassification of younger forests by GNN. There are several reasons for such misclassification errors, including those identified by Davis et al. (n.d.):

> [There] is a tendency for GNN to predict increasing older forest characteristics following forest thinning disturbances. In many cases, this may be a result of the elevated frequency of canopy gaps and shadows generating confusing remote sensing signals instead of an actual increase in old growth structure. Likewise.… rapid ground vegetation re-establishment (green up) in forest stand-replacement events (e.g., high-severity fire) can also result in apparent rapid gains in older forest.

Following Davis et al. (n.d.), we therefore used a high-severity disturbance mask to eliminate such areas from our habitat model. This ensured that once a stand-replacing event affected a pixel, it could not be tallied as "murrelet habitat" in our report because it takes more than 25 years for a young stand to develop into older forest suitable for murrelets.

When assigning losses and gains in our analysis, it is important to consider that losses from severe disturbances are easier to detect spectrally than small incremental gains in nesting habitat (Battles et al. 2018). On the surface, this seems to favor losses and that losses will be quantified at greater rates than gains. Rather, this indicates that there is more error associated with estimating gains in habitat compared to losses. Some of these challenges were alleviated by improvements in the disturbance detection algorithms used in this report, which use a multispectral and multiyear ensemble, as described above. However, it stands that losses of habitat that result in a strongly contrasting spectral signal across years (such as those occurring after clearcut harvests) are more accurately detected than losses in which the spectral contrast is less (such as in some forest thinning operations). Also, gains in habitat due to small increases in tree size are harder to detect. Thus, we caution that our estimates of potential habitat gain and estimates of loss from low-severity disturbance may be less accurate than our estimates of habitat loss from high-severity disturbances.

There can also be inaccuracies when assigning attribution of loss for disturbances. The NWFP monitoring team uses LCMS models to assign disturbances categories (i.e., timber harvest, wildfire, insect damage, and other), based on the magnitude or duration of disturbance events, but some disturbances are incorrectly assigned. As an example, the rapid (<1 year) loss of a forested stand can occur from many disturbance events, such as from timber harvest (i.e., clearcutting, heavy thinning), wildfire, landslides, or severe windthrow events (i.e., uprooting or breakage of trees by wind) following storms. On some federal reserved lands where timber harvest is not permitted and there have been no wildfires, such disturbances are assigned to the “other” disturbance category (which includes windthrow and landslides). However, outside of these land allocations, such fast, high-magnitude disturbances can be assigned erroneously to the timber harvest category. We are aware of several landslide and blowdown events that are classified as timber harvest in our current models. While some of these stands on state and other lands were subsequently salvage logged, and thus truly were harvested, the ultimate cause of the habitat loss was due to another disturbance event and was thus classified incorrectly as due to harvest. Consequently, the acreage estimates of our other disturbance category is lower than expected. Another source of uncertainty in our disturbance data arises from the difficultly in assigning a disturbance type to many events. A substantial proportion of nesting habitat losses have no attributable cause in our analysis. For example, at the NWFP area-wide scale, we documented 220,126 acres of gross habitat loss, but only 162,846 of those acres (74 percent) could be assigned to one of the four disturbance categories (table 11).

Lastly, we stress that map products resulting from models generated at large spatial scales should be used at large scales. Raster datasets by their very nature are approximations of ground conditions and should not be used to assign or predict values for habitat attributes at precise-point locations on the ground. Instead, our habitat model should be applied at large spatial scales, for example, for modeling broad characterizations of forest attributes within multiple watersheds or within a state. The GNN metadata specifically advises users that the most appropriate use of these data is across landscapes, counties, multiple watersheds, or ecoregions (areas much larger than points, stands, or patches). In addition, using our maps as the sole method to locate specific areas of murrelet nesting habitat (or nonhabitat) is inappropriate. Presence or absence of murrelet nesting habitat at fine scales should be ascertained using a combination of methods that include field-based surveys.

Comparisons With Previous Estimates

This report, which estimates murrelet nesting habitat for the first 25 years of the NWFP, uses different source data and methods compared to previous monitoring reports (Huff et al. 2006; Raphael et al. 2011, 2016). In previous monitoring reports, murrelet habitat quantity, distribution, and trend were estimated for the first 10, 15, and 20 years of the NWFP. Each report represented an improvement over the previous reports in terms of advancements in mapping vegetation and characterization of disturbances. Each successive analysis was derived from the best and most up-to-date forest attribute data available at the time. However, these methods differ, and readers should not make comparisons with previous reports without a thorough understanding of the processes used to obtain the different results.

We also expect estimates of acres in different habitat classes to differ among reports due to the methods used to assign habitat class. Our estimates of acres within each habitat class depend on the threshold chosen to separate higher from lower habitat probability. Rather than comparing absolute acres of habitat among reports, we encourage readers instead to focus on comparisons of the trend over time, and on comparisons of relative amounts of habitat among landowners and among various geographic extents. Such comparisons are more meaningful than comparisons of the number of acres.

In this report, we defined the best quality nesting habitat as higher probability habitat that is also core habitat. In previous reports (e.g., Raphael et al. 2016) "higher suitability" was defined as habitat within both the moderate and higher probability classes, and without respect to being core. Here, we estimated that core habitat represented only 140,091 acres across the NWFP area in 1993. Core habitat was especially rare in California, Oregon, and for nonfederal landowners in the NWFP area. In this report, we also observed declines in core habitat for murrelets in Washington and California, but a small net increase in higher probability core habitat in Oregon.

Our observation of small increases in higher probability nesting habitat in Oregon contrasts with declining trends observed in all previous monitoring reports. This new finding is entirely attributable to the new GNN data we obtained for the current report. We verified this by replicating our previous model (Raphael et al. 2016), using that model's covariate sets and Maxent model settings, with the new GNN's covariate values for 1993 and 2017. In contrast to the decline in nesting habitat from 1993 to 2012 observed in the previous report (Raphael et al. 2016), this test showed a small increase in higher probability nesting habitat for the same time period. It is concerning that our current results contrast so sharply from previous results. The modeling team responsible for the new GNN data is confident the current data are more accurate than the previous GNN data.

This report also differs from previous reports because we placed higher emphasis on the effects of nest predation on habitat suitability. Research with this species indicates that nest depredations from corvids are a major threat and should be accounted for in our modeling of nesting habitat. Thus, we placed a greater emphasis on distinguishing landscape habitat pattern in this report. We used the most up-to-date murrelet research available to differentiate between the highest quality core habitat and lower quality edge and scatter habitat, where corvid nest depredations are expected to be higher. We also placed greater emphasis on the impacts of human modifications to the landscape because research has indicated that increased human use of the landscape is associated with decreased habitat suitability for murrelets. For example, in the Redwood National and State Parks, Steller's jays are attracted to human food in campgrounds and occur at higher densities than in backcountry locations (George et al. 2001, Goldenberg et al. 2016, Wallen et al. 1999); Steller's jays are known predators of murrelet eggs and nests in the Redwood National and State Parks (Golightly and Schneider 2011). Thus, we expected that tracts of core habitat with high recreational use would provide lower quality habitat for this species than more remote areas, despite platforms and the availability of large trees. Overall, we felt that greater emphasis was needed on human impacts in our murrelet habitat models, especially as human population density and recreation pressure on public lands increase in the NWFP area.

We expect estimates of absolute acres from one report to the next to differ, at least in part because such estimates are dependent on the threshold chosen to separate higher from lower habitat probability. Although the same method was used to calculate thresholds in our current report, as in Raphael et al. (2016), the exact threshold calculated will vary with each model run. Comparisons of trend over time from one report to another, and comparisons of relative amounts of higher probability nesting habitat among landowners and various geographic extents (states, conservation zones) are more meaningful. With that in mind, our baseline 1993 estimate of moderate probability nesting habitat on all habitat-capable lands (2.53 million acres) is greater than that of Raphael et al. (2016 and 2011 [2.08 and 2.12 million acres, respectively]). Our estimates of higher probability nesting habitat in 1993 (1.51 million acres) is much greater than the estimate in Raphael et al. (2016) (0.46 million acres). In this report, we defined the highest quality habitat as core higher probability nesting habitat, which included only patches of habitat that met the threshold of higher probability and were at least 5.56 acres in size. This is different than Raphael et al. (2016) where the highest quality habitat was habitat that met the threshold of moderate or higher probability, irrespective of patch size. We estimated that core habitat represented only 140,091 acres of the NWFP area in 1993, compared to 456,800 acres in Raphael et al. (2016), and 1.7 million acres in Raphael et al. (2011). In this report, we also observed declines in core habitat for murrelets in Washington and California, but a net increase in core habitat in Oregon. Our observation of increased higher probability nesting habitat in Oregon contrasts with declining trends observed in all previous monitoring reports.

Effects of Climate Change

The climate of the Pacific Northwest is projected to change significantly in the 21st century. Most climate models project warmer and drier summers and wetter winters for forested areas used by murrelets in the NWFP area (Mote et al. 2008, Mote and Salathe 2010, Salathe et al. 2010). Relative to areas further inland, warming is projected to be slower in the areas where murrelets nest due to the Pacific Ocean marine influences. However, high temperatures are expected to be more extreme (Brewer and Mass 2016), and onshore winds are expected to weaken, reducing the marine influence on coastal forests, which generally keeps such forests relatively cool and wet. Warmer spring and summer temperatures are expected to result in hotter droughts and greater tree mortality (Allen et al. 2015), which is already being observed in the Western United States (van Mantgem et al. 2009). This will reduce epiphyte growth on branches, thereby degrading the suitability of platforms for murrelet nesting (van Rooyen et al. 2011).

There are also projected changes to the disturbance ecology of this region. The marine climate associated with the forested areas of the Pacific Northwest is currently considered less prone to dry conditions and wildfire than many forest types in the Western United States. However, climate models predict that drought will increase in this region, except for higher elevations on the Olympic Peninsula and Cascade Mountains (Littell et al. 2013, 2016, 2018). For the Oregon Coast Range and Olympic Mountains, mean burn area is expected to increase by a factor of 3.8 compared to the 1980–2006 period (Littell et al. 2010). Predictions for the 21st century are that most of the area west of the Cascade Range in Washington and Oregon will experience wildfires, and the percentage of area burned will approach 100 percent, except along the Pacific coastline and at high elevations (Sheehan et al. 2015). Even forests at higher elevations are predicted to experience wildfires (Davis et al. 2017). Models indicate that warmer and drier summers will produce more frequent, high-severity fires, thus reducing the extent and connectivity of late-seral/old-growth forests, almost certainly resulting in negative consequences for the murrelet (Littell et al. 2013, Wan et al. 2019). Currently, timber harvest is the leading cause of attributable nesting habitat loss on nonfederal lands. While many forest management schemes that are used in drier forests, such as surface and canopy thinning, can reduce the occurrence and effects of high-severity fires in those forest types, these activities may not be effective in coastal forests (Lindenmayer et al. 2009). Moreover, they may have negative consequences for murrelets, which nest in closed-canopy forests.

Regional models vary in projections of winter precipitation, with topography and marine influences playing large roles. Across the region, however, the vast majority of models project increased precipitation during the winter (as much as 42 percent) (Mote and Salathe 2010), with more intense daily precipitation events over the complex terrain in western Washington (Salathe et al. 2010). Winter precipitation is expected to consist of rain rather than snow; and as a result, low-elevation forests will experience more severe or longer duration water limitations in the summer because of diminished snowpack. This is also expected to result in decreased seedling regeneration and tree growth because the timing of the majority of precipitation is outside of the growing season (Littell et al. 2013). There are also concerns about insect outbreaks. Native bark beetles have evolved with conifer forests of North America; however, when climatic conditions are conducive and an outbreak occurs, tree mortality rates rise and in some cases can result in tree and plant association replacements (Bentz et al. 2010). Climatic variables within the range of the murrelet are currently unsuitable for outbreaks of bark beetles (Littell et al. 2010). This may change as projected warmer temperatures translate to less winter beetle mortality and disruption of the beetle's life cycle (Bentz et al. 2010). Trees that are stressed, such as by drought, are more susceptible to mass attack (Bentz et al. 2010, Halofsky et al. 2011).

These combined effects are expected to diminish nesting habitat for murrelets in the Pacific Northwest in the coming century. Rogers et al. (2011) evaluated several climate simulations and found that under two of three simulations, most of the forests within the range of the murrelet is expected to transition from maritime to temperate and drier forest types. These findings are supported by Halofsky et al. (2011) and Sheehan et al. (2015), who found that vegetation is predicted to change from conifer to mixed forests during the 21st century. It is worth noting that the redwood forests of coastal northern California are closely associated with summer marine fog, and there is evidence that fog frequency has decreased over the past century. Coastal redwood and other coastal ecosystems in the murrelet's range may be increasingly drought stressed under a summer climate of reduced fog (Johnstone and Dawson 2010). The disturbance ecology is expected to change dramatically with more area burned in wildfire (Wan et al. 2019). The timing and extensiveness of these predicted changes differ depending upon the climate scenario used, but the consensus is that the shift from coniferous to mixed forest is expected to begin in the south and expand northward along the coast and upslope (Sheehan et al 2015). For an at-risk species that relies on contiguous and mature coniferous forests for nesting, such as the murrelet, these modeled climate scenarios suggest that a reduction in amount of suitable nesting habitat for murrelets will occur during this century.

Implications of Results

Among its many objectives, the NWFP was designed to provide habitat conditions that support a viable and well-distributed population of murrelets. The NWFP is a long-term strategy that is expected to reach its full potential after many decades when previously cutover forest stands in federal reserves mature and function as nesting habitat. In the short term, the NWFP objective is to conserve remaining habitat in federal reserves. We found that this objective was being met for higher probability nesting habitat, but not for core habitat. We estimated that there was a small increase in higher probability nesting habitat on federal reserved lands from 1993 to 2017, although there was a 1,935-acre net decline in core habitat. Losses in core habitat were attributed mostly to wildfire (549 acres), but also occurred from timber harvest (451 acres) and other disturbances (410 acres). We stress that future efforts seeking to conserve murrelet habitat consider landscape habitat pattern. The creation and maintenance of large, unfragmented patches of suitable nesting habitat would likely augment future conservation efforts. This could be done, for example, by allowing younger stands adjacent to old- or mature-growth core habitat to age and develop platforms. In addition, land managers could consider providing buffers surrounding existing murrelet habitat to reduce risk of blowdown and other negative edge effects. Given the amount of habitat-capable lands in the NWFP area, there is great potential to create more core murrelet habitat if losses from timber harvest (for all landowners, but primarily for state and other landowners) and wildfire (for all landowners) can be reduced.

Federal reserves contain 5.8 million acres of habitat-capable lands. We estimated that they contained 987,347 acres of higher probability nesting habitat in 2017, with 118,613 acres of that being core. Thus, there is the potential for almost 5 million additional acres of federal reserves to grow into murrelet habitat if losses can be checked. There is even greater potential for the development of core habitat. As we comment elsewhere, it may take many decades to see this potential realized. Cutover forests that were composed of younger trees in 1993 will not have grown platforms in 25 years. Old-growth characteristics, such as platforms, require about 175 to 200 years to develop in most conifer species in the Pacific Northwest (Franklin et al. 1981, Old Growth Definition Task Group 1986). It is also important to consider that the majority of higher probability nesting habitat in federal reserves, as well as on other lands, was classified as edge and scatter in our models. For murrelet recovery, more core habitat is needed on all lands, and we expect that the time required to develop appreciable acreage of core habitat will take much longer across all ownerships. In the short term, protecting all murrelet habitat could provide the most benefit. In addition, conservation efforts that focus on protecting higher probability nesting habitat will benefit this species, as will management efforts that enlarge the size of tracts of core habitat. This will help reduce the negative consequences of habitat fragmentation. Moreover, enhancing moderate probability nesting habitat will produce more contiguous, unfragmented landscapes and should benefit murrelets, which currently occupy a very small portion of the landscape, even in federal reserves.

We also caution that logging adjacent to moderate and higher probability nesting habitat may negatively impact this species, as this will increase the exposure of core habitat and create edge habitat. There are many downsides to an increase in edge habitat, including lower moss abundance (important for nest platforms) due to wind exposure, higher temperature, and lower moisture retention (van Rooyen et al. 2011). Nests near edges are also at increased risk from predation, as discussed earlier in this report and are more susceptible to windthrow. Windthrow is a natural phenomenon and an important disturbance agent in coastal forests of the Pacific Northwest, but it can increase following clearcutting or thinning. This is true even of lighter thins. The magnitude of the effect depends on factors such as topography and tree height-to-diameter ratios (Harrington et al. 2005, Roberts et al. 2007, Wilson and Puettmann 2007). Even thinning operations designed to accelerate the development of murrelet nesting habitat in the long term (e.g., Maguire et al. 1994) can have significant short-term negative impacts to murrelets, and this should be considered in management decisions (McShane et al. 2004). One conservation measure that is commonly used to minimize negative effects of forest edges is to provide forested buffers (USDI FWS 1997). The murrelet recovery plan includes maintaining and enhancing buffer habitat around nesting habitat as a recovery action and suggests minimum buffer widths of 300 to 600 ft (USDI FWS 1997). Such mitigation actions may help protect interior tracts of core habitat for this threatened species.

While the NWFP was developed to guide federal land management, nonfederal entities manage the majority (66 percent) of habitat-capable acres across the NWFP area. Thus, nonfederal landowners have the potential to make great contributions to murrelet recovery, particularly if losses of nesting habitat from timber harvest can be curtailed. As habitat quality and quantity on federal reserves increase, less reliance on nonfederal lands may be warranted. However, in some parts of the NWFP area, such as where federal and nonfederal lands are checkerboarded or otherwise intermingled, maintaining large tracts of core habitat will require long-term commitments from all landowners. Thus, for murrelet recovery, we encourage incentives for nonfederal landowners to reduce the harvest of moderate and higher probability nesting habitat. There are limits on the extent to which the NWFP can contribute to murrelet recovery because it directs only one-third of the management of habitat-capable lands within the NWFP area.

Although we did not detect an obvious correlation between recent murrelet population size and estimated amount of higher probability nesting habitat at the coarse scales of states and conservation zones, we did observe positive relationships between murrelet at-sea abundance and change in amount of higher probability nesting habitat at those coarse scales. This finding, although not direct evidence of a cause-effect relationship, does lend support to the idea that forest practices that conserve and restore habitat will likely contribute importantly to murrelet recovery. We found that most core habitat was within reserves and therefore maintaining the existing system of late-successional reserves will be critical to conservation and restoration of murrelet habitat on federal lands. If losses of nesting and core habitat are reduced, old forest suitable for nesting is allowed to develop, fragmentation of older forest is reduced throughout the reserved federal lands, and all current habitat is buffered from disturbance effects, then meeting NWFP objectives would likely be more certain. However, even on reserved lands, there are risks to murrelet habitat from timber harvest (including thinning), wildfire, and other natural disturbances, which may be exacerbated by climate change. Given declining murrelet population trends in the northern part of the listed range, as well as the continued habitat losses there, it is uncertain whether that population will persist to benefit from potential future increases in nesting habitat. The declining trend for murrelet populations (McIver et al. 2021) and higher probability nesting habitat in Washington underscores the need to arrest the loss of nesting habitat there. We also identified a need for greater protections (including buffers) for current tracts of moderate and higher probability nesting habitat, not only in federal reserves in Washington, but across the species' listed range as a result of uncertainties about future trends in murrelet numbers and nesting habitat related to climate change, including but not limited to likely increases for catastrophic fires.

We discuss in detail above projected changes to murrelet habitat due to climate change. Climate change will likely result in losses of existing murrelet nesting habitat at a scale that managers have not experienced to date. In addition to causing changes in forest composition, climate change is expected to change the disturbance ecology of coastal forests, with increases in fire and insect damage (e.g., Wan et al. 2019). Current losses from fire and insects are much lower than losses to timber harvest. Considering all threats to terrestrial habitat together, we find it difficult to be optimistic about the recovery of marbled murrelet in the near future without major changes in land management. We identified the following as the most urgent changes needed to improve the prognosis for murrelet recovery: (1) continued management of current NWFP reserves to protect existing nesting habitat and grow new habitat, (2) incentives to motivate state, tribal, and private landowners to protect existing nesting habitat and grow new habitat, and (3) consideration by all landowners to address the threats posed by climate change. Over many years (>200 years), as forests within federal reserves age into suitable habitat, the prognosis may be better, but continued monitoring will be important for assessing whether the NWFP is contributing to recovery of the marbled murrelet.

Suggestions for Future Research

We recommend several lines of future research that may help improve the quality of models of marbled murrelet nesting habitat:

- We have used the software package Maxent in this and previous modeling projects, and while we did explore the utility of other modeling platforms, such as Maxlike and Random Forest, further exploration of alternative modeling platforms is warranted.
- We see value in exploring additional covariates to better characterize marbled murrelet nesting habitat. In past efforts, we evaluated topographic attributes, such as slope, aspect, and topographic position, and we had included certain climatic attributes. Further work to explore such variables may lead to improved models.
- We also recommend use of multiscale optimization (e.g., McGarigal et al. 2016, Timm et al. 2016, Wan et al. 2018) to explore the best spatial resolution for each of the covariates used in habitat models.
- Exploring reliable methods to validate results of habitat models is needed. In this current effort, we observed some geographic areas where model results did not seem to conform with on-the-ground observations. It would be valuable to develop methods to make objective comparisons with model projections versus independent measures of habitat quality. Evaluating additional sources of forest cover information for comparison with GNN data will be an important element of this validation work. Light detection and ranging (LiDAR) is one such source, but LiDAR data is not available for the entire model area, and thus will be most useful for targeted comparisons in limited geographic areas. Another source of vegetation structure data is from the National Agriculture Imagery Program photogrammetric point cloud data, which does cover the entire murrelet range and warrants exploration.
- Developing models to project forest habitat structure and climate effects into the future would enable more robust forecasts about how habitat quality might change over coming decades given various assumptions about forest disturbance and land management actions. Such projections could provide a useful tool to evaluate consequences of each scenario on murrelet habitat quality and population viability.

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Metric Equivalents

When you know:	Multiply by:	To get:
Inches (in)	2.54	Centimeters (cm)
Inches (in)	25.4	Millimeters (mm)
Feet (ft)	0.305	Meters (m)
Miles (mi)	1.609	Kilometers (km)
Square miles (mi^2)	2.59	Square kilometers (km^2)
Acres (acre)	0.405	Hectares (ha)

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