Marbled Murrelet (*Brachyramphus marmoratus*)
Northern California Climate Change Vulnerability Assessment Synthesis

An Important Note About this Document: *This document represents an initial evaluation of vulnerability for marbled murrelet in northern California based on expert input and existing information. Specifically, the information presented below comprises vulnerability factors selected and scored by regional experts, relevant references from the scientific literature, and peer-review comments and revisions (see end of document for a glossary of terms and brief overview of study methods). The aim of this document is to expand understanding of habitat vulnerability to changing climate conditions, and to provide a foundation for developing appropriate adaptation responses.*

Peer review for this document was provided by Gregory Schrott (U.S. Fish and Wildlife Service). Vulnerability scores were provided by Richard Golightly (provided additional comments; Humboldt State University) and Gregory Schrott.

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Species Description

The marbled murrelet (*Brachyramphus marmoratus*) is a small seabird in the Alcidae family, and is distributed during the breeding season from Santa Cruz, California north through the Aleutian Islands of Alaska (Carter & Erickson 1992; Mendenhall 1992; Raphael et al. 2018). Marbled murrelets forage on small schooling fish and krill within the nearshore marine environment (Golightly et al. 2004), typically within 3 km (2 mi) of the coast (Carter & Erickson 1992; Raphael et al. 2018). Their nesting habitat lies inland within mature and old-growth forests often dominated by coast redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga heterophylla*; Binford et al. 1975; Carter & Erickson 1992; Hamer & Nelson 1995; Meyer et al. 2004; Baker et al. 2006; Hébert & Golightly 2006; Golightly et al. 2009). Habitat characteristics typically associated with marbled murrelet nesting sites include the presence of nesting platforms of moss, ferns, or other epiphytes located on branches or broken treetops in large-diameter trees; adequate canopy cover over the nest; and proximity to the marine environment (Binford et al. 1975; Hamer & Nelson 1995; Meyer et al. 2004; Baker et al. 2006; Hébert & Golightly 2006; Golightly et al. 2009). In northern California, most nests are built in coast redwood trees (Golightly et al. 2009) within 38.5 km (24 mi) of the coast (Raphael et al. 2018), and nesting sites are frequently located on gentle, low-elevation slopes or alluvial flats near streams (Hamer & Nelson 1995; Meyer et al. 2004; Baker et al. 2006; Raphael et al. 2018).

Executive Summary

The relative vulnerability of marbled murrelet in northern California was evaluated as moderate-high by regional experts due to moderate-high sensitivity to climate and non-climate stressors, moderate exposure to projected future climate changes, and moderate adaptive capacity.

Marbled Murrelet	Rank	Confidence
Sensitivity	Moderate-High	High
Future Exposure	Moderate	High
Adaptive Capacity	Moderate	High
Vulnerability	**Moderate-High**	**High**

Sensitivity & Exposure Summary	
	Climate and climate-driven factors: • Air temperature, ocean temperature, precipitation amount and timing, drought, heat waves *Disturbance regimes*: • Wildfire, wind *Non-climate stressors*: • Roads and trails, recreation, timber harvest, pollution

The marbled murrelet is sensitive to climate stressors and disturbance regimes that impact survival and reproductive success in a variety of ways. For instance, changes in air temperature, precipitation, and drought may reduce the quality and/or availability of nesting habitat by altering forest structure, including epiphyte growth. Heat waves could increase thermal stress, particularly in fledglings, while windthrow associated with storms may result in the loss of mature nest trees. Because marbled murrelets are dependent on both marine and terrestrial environments, they are also vulnerable to changes in ocean temperature that impact prey availability. Finally, uncharacteristically severe wildfires could result in the loss of nesting habitat and increase habitat fragmentation. In addition to climatic sensitivities, marbled murrelets are also impacted by the presence and use of roads and trails, recreational activity, timber harvest, and pollution (e.g., oil spills). Human activity around roads and recreational areas, in particular, are associated with increases in populations of corvid nest predators (e.g., jays, ravens). Timber harvest has been the primary driver of habitat loss across the species range, while oil spills in foraging areas can cause high rates of mortality in foraging birds.

<table>
<tr>
<td rowspan="2">Adaptive Capacity Summary</td>
<td><u>Factors that enhance adaptive capacity</u>:
+ Some indication of stabilization or increases in California populations
+ Foraging strategies adapted to variable marine environments
+ High societal investment in conservation over the last two decades</td>
</tr>
<tr>
<td><u>Factors that undermine adaptive capacity</u>:
– Extensive loss and fragmentation of nesting habitat, contributing to population declines
– Low reproductive rates and high site fidelity, which increase potential for breeding disruptions
– Low potential for management of prey availability within marine environments</td>
</tr>
</table>

Marbled murrelets have declined significantly across their range and were listed as federally threatened in 1992 under the Endangered Species Act, largely due to the loss of nesting habitat and increased nest predation in and around fragmented old-growth stands. Low reproductive rates and high site fidelity also influence vulnerability to population declines; however, marbled murrelets demonstrate some flexibility in their foraging strategies in response to variable prey availability and changing energy needs during the breeding season. Over the past several decades, societal support for marbled murrelet conservation has been significant, and has included the creation and implementation of the Northwest Forest Plan that highlights protection of nesting habitat as a management priority across the Pacific Northwest. Most management strategies for marbled murrelets focus on protecting and enhancing terrestrial nesting habitat, in part because little can be done to increase prey availability within marine environments aside from limiting the risk of anthropogenic impacts.

Sensitivity and Exposure

Marbled murrelets were evaluated by regional experts as having moderate-high overall sensitivity (high confidence in evaluation) and moderate overall future exposure (high confidence) to climate and climate-driven factors, changes in disturbance regimes, and non-climate stressors.

There are no available projections that model potential shifts in marbled murrelet distribution over the coming century. However, it is likely that climate change will alter the future distribution of this species by impacting marine prey availability and/or the quality and availability of nesting habitat (USFWS 2009; Vuln. Assessment Reviewer, pers. comm., 2018).

Potential Changes in Species Distribution
• No projections available for projected future shifts in marbled murrelet distribution • Changes in the distribution or abundance of predators would likely impact murrelet populations
Source(s): USFWS 2009; Vuln. Assessment Reviewer, pers. comm., 2018

Changes in climate conditions could also contribute to shifts in the distribution and abundance of predators, which would likely to impact murrelet populations (Vuln. Assessment Reviewer, pers. comm., 2018).

No areas of potential refugia have been identified for marbled murrelets (Vuln. Assessment Reviewer, pers. comm., 2018). However, wet coastal forests may be more stable than drier inland forests as climate conditions change, potentially reducing the impacts of projected regional increases in fire activity on marbled murrelets (Vuln. Assessment Reviewer, pers. comm., 2018).

Sensitivity and future exposure to climate and climate-driven factors

Regional experts evaluated marbled murrelets as having moderate-high sensitivity to climate and climate-driven factors (moderate confidence in evaluation), with an overall moderate-high future exposure to these factors within the study region (moderate confidence). Key climatic factors that affect marbled murrelets include air temperature, ocean temperature, precipitation amount and timing, drought, and heat waves.[1]

Air temperature

The distribution of occupied marbled murrelet nesting sites is closely correlated with cooler maximum summer temperatures (Meyer et al. 2004). However, it is currently unknown whether marbled murrelets exhibit physiological sensitivity to temperature, or whether the association between temperature and occupied nesting sites is primarily due to the effect of cooler microclimates on epiphyte growth (Meyer et al. 2004; Vuln. Assessment Reviewer, pers. comm., 2018).

Air temperature affects nesting habitat quality (e.g., availability of large trees and nesting platforms) by impacting forest structure and the distribution of conifer species utilized by marbled murrelets for nesting (DellaSala et al. 2015; Vuln. Assessment Reviewer, pers. comm., 2018). However, warmer temperatures are likely to impact redwood forests and Douglas-fir forests differently (Vuln. Assessment Reviewer, pers. comm., 2018). In coastal redwood forests, warmer summer minimum temperatures have been correlated with increased radial growth within northern populations where growth is not water-limited (Carroll et al. 2014). By contrast, redwood growth is negatively correlated with spring or summer maximum temperature in the drier central and southern portions of their range (Carroll et al. 2014, 2018), likely due to enhanced drought stress as a result of increasing evaporative demand (Flint & Flint 2012). In forests dominated by Douglas-fir, increased water stress due to enhanced evaporative demand is a significant driver of growth declines (Irvine et al. 2009; Restaino et al. 2016) and tree mortality (van Mantgem et al. 2009; Restaino et al. 2016). Relatively small increases in mean temperatures (especially winter temperatures) may also have significant impacts on epiphyte

[1] Climate and climate-driven factors presented are those ranked as having a moderate or higher impact on this species; additional climate and climate-driven factors that may influence the species to a lesser degree include storms.

occurrence (Glavich et al. 2005; Geiser & Neitlich 2007), potentially reducing nest platform availability for marbled murrelets.

<table>
<tr><th colspan="2">Regional Air Temperature Trends[2]</th></tr>
<tr><td>Historical & current trends:
0.2°C (0.4°F) increase in the average annual temperature between 1900 and 2009 for the Northwestern California ecoregion (Rapacciuolo et al. 2014)
No seasonal temperature trends available</td><td>Projected future trends:
2.2–5.2°C (4.0–9.4°F) increase in the average annual temperature by 2100 (compared to 1951–1980) for the North Coast ecoregion (Flint et al. 2013; Flint & Flint 2014)
1.9–4.5°C (3.4–8.1°F) increase in average winter minimum temperatures
2.3–6.1°C (4.1–11.0°F) increase in average summer maximum temperatures</td></tr>
<tr><th colspan="2">Summary of Potential Impacts on Species (see text for citations)</th></tr>
<tr><td colspan="2">Changes in the quality and availability of nesting habitat due to the impacts of temperature on epiphyte growth, conifer distribution, and forest structure</td></tr>
</table>

Ocean temperature

Sea surface temperatures are strongly related to ocean productivity, with cooler water supporting greater prey availability for seabirds (Ainley et al. 1993; Santora et al. 2014; McClatchie et al. 2016). As ocean temperatures increase over the coming century, changes in prey distribution and availability are likely (USFWS 2009; Lorenz et al. 2016). These changes may, in turn, impact marbled murrelet survival and reproductive success (USFWS 2009; Vilchis et al. 2015; Lorenz et al. 2017; Vuln. Assessment Reviewer, pers. comm., 2018). However, the impacts of sea surface temperature on prey are complex and further complicated by the multiple trophic levels between phytoplankton and higher-level predators like the marbled murrelet (Lorenz et al. 2016).

In northern California, periods of anomalously-warm ocean temperatures are often associated with large-scale patterns of climate variability, such as the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO; Bond et al. 2015; McClatchie et al. 2016; Fiedler & Mantua 2017), although warm events are not always associated with these phenomenon (Fiedler & Mantua 2017). The California Current System experienced an unprecedented marine heat wave from 2014–2016, likely due to a combination of unusually-warm conditions in the tropical Pacific and a strong El Niño event that occurred in 2015–2016 (Bond et al. 2015; Leising et al. 2015; McClatchie et al. 2016; Jacox et al. 2018). The heat wave was associated with poor

[2] Trends in climate factors and natural disturbance regimes presented in this and subsequent summary tables are not species-specific; rather, they represent broad trends and future projections for the study region. The precipitation, temperature, climatic water deficit, and snowpack projections for this project are derived from the Basin Characterization Model, which uses modified Jepson ecoregions (Flint et al. 2013; Flint & Flint 2014). Projections for all other factors are based on a review of relevant studies in the scientific literature. For this project, exposure was evaluated by calculating the magnitude and direction of projected change within the modified Jepson ecoregions that include habitat distribution within the study geography.

productivity and shifts towards warm-water species at lower trophic levels, which reduced foraging habitat quality for seabirds and other predators (McClatchie et al. 2016; Wells et al. 2017). During this period, several major seabird mortality events also occurred, with large numbers of Cassin's auklets (*Ptychoramphus aleuticus*), common murres (*Uria aalge*), and rhinoceros auklets (*Cerorhinca monocerata*) washing up on beaches during the 3-year heat wave (Garfield & Harvey 2016; Harvey et al. 2018; Jones et al. 2018).

<table>
<tr><th colspan="2">Regional Ocean Temperature Trends</th></tr>
<tr><td>Historical & current trends:
0.7°C (1.3°F) increase in global sea surface temperature between 1900 and 2016 (Huang et al. 2014; Jewett & Romanou 2017), including significant warming in the California Current System (Alexander et al. 2018)</td><td>Projected future trends:
1.3–2.7°C (2.3–4.9°F) increase in global sea surface temperatures by 2100 (compared to the 1990s; Bopp et al. 2013; Jewett & Romanou 2017)
2–4°C (3.6–7.2°F) increase in sea surface temperature by 2100 (compared to 1920–2016) for the California Current System (Alexander et al. 2018; Sievanen et al. 2018)</td></tr>
<tr><th colspan="2">Summary of Potential Impacts on Species (see text for citations)</th></tr>
<tr><td colspan="2">Changes in prey distribution and availability, potentially affecting murrelet survival and reproductive success
Large mortality events possible during periods of extreme warm temperatures</td></tr>
</table>

Precipitation amount and timing and drought

Changes in precipitation and increased drought are likely to alter patterns of plant moisture stress in coastal forests (Johnstone & Dawson 2010; Flint & Flint 2012; Carroll et al. 2014), which are characterized by frequent fog that relieves summer drought stress and closed canopies that create cool, moist microclimates (Olson et al. 1990; Johnstone & Dawson 2010; Mooney & Dawson 2016). These conditions support the growth of epiphytes that provide nest platforms for marbled murrelets (Sillett & Van Pelt 2007). Drier conditions may reduce the suitability of nesting habitat by impacting plant growth and mortality (USFWS 2009; Raphael et al. 2018; Vuln. Assessment Reviewer, pers. comm., 2018). For instance, many epiphytes within coastal redwood forests are sensitive to desiccation, and changes in microclimate conditions due to reduced precipitation and/or increased drought would likely limit epiphyte growth and distribution (Glavich et al. 2005; Sillett & Van Pelt 2007), decreasing the availability of nesting platforms (Vuln. Assessment Reviewer, pers. comm., 2018).

Water stress associated with greater evaporative demand and warmer and more extreme droughts have already contributed to increases in tree mortality rates across the western U.S. (van Mantgem et al. 2009). Reduced vigor in drought-stressed trees may also increase their vulnerability to wildfire, outbreaks of insect pests, and disease (Kliejunas 2011; van Mantgem et al. 2013; Millar & Stephenson 2015), especially as hotter droughts become more common (Millar & Stephenson 2015).

Regional Precipitation & Drought Trends	
Historical & current trends: • 7.2 cm (2.8 in) increase in mean annual precipitation between 1900 and 2009 for the Northwestern California ecoregion (Rapacciuolo et al. 2014) • Drought years have occurred twice as often over the last two decades compared to the previous century (Diffenbaugh et al. 2015) • 2012–2014 drought set records for lowest precipitation, highest temperatures, and most extreme drought indicators on record (Griffin & Anchukaitis 2014; Diffenbaugh et al. 2015)	*Projected future trends:* • 20% decrease to 27% increase in mean annual precipitation on the North Coast by 2100 (compared to 1951–1980) for the North Coast ecoregion (Flint et al. 2013; Flint & Flint 2014)[3] • Seasonal changes are projected to be more significant as the wet season becomes wetter and shorter (i.e., later onset of fall rains and earlier onset of summer drought) and the dry season becomes drier and longer (Pierce et al. 2018; Swain et al. 2018) • Overall, interannual variability is expected to increase (Pierce et al. 2018; Swain et al. 2018) • Drought years are twice as likely to occur over the next several decades due to increased co-occurrence of dry years with very warm years (Cook et al. 2015) • 80% chance of multi-decadal drought by 2100 under a high-emissions scenario (Cook et al. 2015) • Severe droughts that now occur once every 20 years will occur once every 10 years by 2100 and once-in-a-century drought will occur once every 20 years (Pierce et al. 2018)
Summary of Potential Impacts on Species *(see text for citations)*	
• Increased plant water stress, resulting in changes to plant growth and forest structure that may impact nesting habitat suitability • Increased risk of tree mortality due to drought or secondary stressors (e.g., wildfire, insects, disease)	

Heat waves

Little information is available regarding the impacts of heat waves on marbled murrelets. However, it is likely that more frequent and/or more severe heat waves would cause thermal stress and dehydration in nestlings, potentially impacting reproductive success (Raphael et al. 2018; Vuln. Assessment Reviewer, pers. comm., 2018).

Regional Heat Wave Trends	
Historical & current trends: • Increase in the frequency of humid nighttime events over the past several decades	*Projected future trends:* • Increased heat waves, with the greatest increase in humid nighttime heat waves and in

[3] Projections for changes in seasonal precipitation can be found at in the full climate impacts table (https://bit.ly/2LHgZaG).

Regional Heat Wave Trends	
(Gershunov & Guirguis 2012) • High interannual and interdecadal variability in heat waves (Gershunov & Guirguis 2012)	coastal areas (Gershunov & Guirguis 2012) • 2–6°C (3.6–10.8°F) increase in the temperature of the hottest day of the year by 2100 (Pierce et al. 2018)
Summary of Potential Impacts on Species *(see text for citations)*	
• Possible impacts to reproductive success due to thermal stress and dehydration in nestlings	

Sensitivity and future exposure to changes in natural disturbance regimes

Regional experts evaluated marbled murrelets as having moderate-high sensitivity to changes in natural disturbance regimes (high confidence in evaluation), with an overall moderate future exposure to these stressors within the study region (high confidence). Key natural disturbance regimes that affect marbled murrelets include wildfire and wind.[4]

Wildfire

The cool, moist microclimate within coastal forests has historically limited the extent of severe fire (Stuart & Stephens 2006), although low-intensity surface fires are frequent (Stuart & Stephens 2006; Lorimer et al. 2009). Larger, more severe fires generally take place during drought periods and/or under the influence of warm, dry east winds (Stuart & Stephens 2006). Coast redwoods have a number of adaptations that allow them to survive fire (e.g., thick bark, the ability to resprout; Lorimer et al. 2009).

Warmer, drier conditions over the coming century are likely to alter fire frequency (Westerling et al. 2011), and intense fires may occur during increasingly severe and/or prolonged periods of drought (Keyser & Westerling 2017). Uncharacteristically severe fires, in particular, can result in the loss of large areas of coastal old-growth forests utilized as nesting habitat for marbled murrelets, particularly at drier inland sites (USFWS 2009; Falxa & Raphael 2016; Raphael et al. 2018). The risk of severe fires is also increased in old-growth stands surrounded by dense forest dominated by small-diameter conifers and broadleaf trees, which increase fuel availability and continuity (Stuart & Stephens 2006). Young stands also have a drier microclimate compared to older forests (Olson et al. 1990; Stuart & Stephens 2006), which increases the risk of intense fires (Stuart & Stephens 2006).

Regional Wildfire Trends	
Historical & current trends: • 85% of U.S. Forest Service lands in northern California are burning less frequently compared to pre-1850 fire return intervals, largely due to fire suppression (Safford & Van de Water 2014)	*Projected future trends:* • State-wide, up to 77% increase in mean annual area burned and 50% increase in the frequency of extremely large fires (>10,000 ha) by 2100 (Westerling 2018) ○ Less significant increases or possible

[4] All disturbance regimes presented were ranked as having a moderate or higher impact on this species.

Regional Wildfire Trends	

• Changes in fire size, area burned, and fire frequency over the past several decades remain well below historical tribally-influenced frequency and extent of burning in California (Stephens et al. 2007)
• No significant trends in the average areal proportion of high-severity fire were documented in northwestern CA from 1984–2008 (Parks et al. 2015; Law & Waring 2015; Keyser & Westerling 2017)
   ○ The relatively short period of record for fire severity data may obscure long-term trends
   ○ To date, there are no peer-reviewed studies on trends in northern California fire severity that include data from the last ten years
	decrease along the North Coast (Westerling et al. 2011)
	• Little projected change in fire severity in northwestern California by 2050 in models based solely on historical fire-climate relationships (Parks et al. 2016)
	   ○ However, human activity and fuel buildup from decades of fire suppression have altered historical fire-climate relationships (Taylor et al. 2016; Syphard et al. 2017; Wahl et al. 2019), and projections that incorporate these factors suggest that more significant increases in fire severity and size may occur (Mann et al. 2016; Wahl et al. 2019)
	• The majority of impacts to natural and human ecosystems come from extreme fire events (i.e., fires that have a low probability of occurring in any given place and time), which are likely to increase over the coming century (Westerling 2018)
	   ○ Generally, these patterns are not well-represented in studies that evaluate indices of mean fire size, intensity/severity, etc.

Summary of Potential Impacts on Species *(see text for citations)*	
• Possible loss of large areas of coastal old-growth forests utilized as nesting habitat • Greater risk of severe fire occurring during periods of drought and in old-growth stands surround by dense second-growth forest	

Wind

Wind damage is rarely associated with redwood mortality due to their ability to sprout from epicormic buds on their trunk and stems (Sillett & Van Pelt 2007; Lorimer et al. 2009; Van Pelt et al. 2016). Injuries to the branches and tree canopy during wind events can allow sprouting and the development of reiterated branches and trunks in the resulting canopy gaps (Sawyer et al. 2000; Sillett & Van Pelt 2007; Van Pelt et al. 2016). The resulting complex structure is able to support the development of arboreal soil and promote epiphyte growth, increasing the availability of potential marbled murrelet nest sites (Sillett & Van Pelt 2007; Sillett et al. 2018).

Changes in the intensity, duration, and frequency of storm events in the region may increase windthrow, particularly at the edge of clearcuts (Sinton et al. 2000) and/or in waterlogged soils (Olson et al. 1990; Lorimer et al. 2009). This, along with flooding, landslides, and other disturbances associated with winter storms, may cause the loss of mature trees or limbs used for nesting (USFWS 2009; Raphael et al. 2018; DellaSala et al. 2018). Increased wind velocity may also contribute to nest failures where eggs or chicks are blown out of nest trees (Vuln. Assessment Reviewer, pers. comm., 2018).

Within marine foraging areas, increased offshore wind velocity could influence patterns of upwelling, potentially impacting prey availability (Bakun 1990; Snyder et al. 2003; Largier et al. 2010; Bakun et al. 2015).

Regional Wind Trends	
Historical & current trends: • Alongshore winds increased from 1940-1990 (Bakun 1990; Schwing & Mendelssohn 1997; Mendelssohn & Schwing 2002) • No trends available for storm-related wind events	*Projected future trends:* • Winds are expected to increase in all seasons, particularly in summer and fall, due to increasing differences in land-ocean pressures and temperatures (Bakun 1990; Snyder et al. 2003; Auad et al. 2006; Largier et al. 2010) • No projections available for storm-related wind events
Summary of Potential Impacts on Species *(see text for citations)*	
• Development of reiterated branches and trunks following injury to redwood trees, enhancing the development of old-growth characteristics that provide nesting sites • Potential loss of nest trees and/or limbs due to storm-related damage • Altered patterns of upwelling due to increased offshore winds, likely impacting prey availability with uncertain effects on murrelets	

Dependency on habitat and/or other species

Regional experts evaluated marbled murrelets as having high dependency on sensitive habitats (high confidence in evaluation) and high dependency on prey or forage species (high confidence). In general, marbled murrelets were evaluated as having a high degree of specialization (high confidence).

Marbled murrelets are dependent on both marine foraging habitats and terrestrial nesting habitats, increasing their vulnerability to climate changes, disturbances, and anthropogenic stressors that affect habitat quality and/or availability in either environment (USFWS 2009; Raphael et al. 2018). Because they have little ability to utilize second-growth forests for nesting, murrelets are highly dependent on mature or old-growth coastal forests (Golightly et al. 2009; USFWS 2009; Raphael et al. 2018), the most important structural characteristic within their nesting habitat is the availability of large-diameter trees with branches or broken tops that can support nest platforms of moss, ferns, and other epiphytes (Hamer & Nelson 1995; Nelson 1997). Thus, marbled murrelets are very sensitive to the loss or fragmentation of their nesting habitat and changes in microclimate conditions that impact moss and epiphyte growth (USFWS 2009; Raphael et al. 2018; Vuln. Assessment Reviewer, pers. comm., 2018). Additionally, the development of a forest structure that includes the habitat elements required to support marbled murrelet reproduction can take 150-250 years, so suitable habitat can be eliminated much faster than it is created (USFWS 1997; Raphael et al. 2018).

Marbled murrelets in northern California forage in nearshore waters by diving in pursuit of small schooling fish, preying on species such as the sand lance (*Ammodytes hexapterus*), anchovy (family *Engraulidae*), herring (*Clupea pallasii*), and juvenile rockfish (*Sebastes* spp.; Burkett 1995; Nelson 1997). The topography and bathymetric characteristics of the region (e.g., a narrow continental shelf) appears to concentrate foraging murrelets within 1.6 km (0.9 mi) of shore, and they likely move along the shore within a roughly 25 km (15.5 mi) range in search of prey rather than traveling farther out to sea (Hébert & Golightly 2008). Although their diet is not well-understood, they may be able to compensate for changing ocean conditions by switching to other species when their preferred prey are scarce (Lorenz et al. 2017; Vuln. Assessment Reviewer, pers. comm., 2018). However, all marine prey are influenced by the same ocean conditions, so their prey base is likely to be impacted by climate changes even if they exhibit generalist tendencies (Vuln. Assessment Reviewer, pers. comm., 2018).

The quality of marine foraging habitat is strongly impacted by ocean conditions (e.g., sea surface temperature) that affect the timing and strength of wind-driven upwelling within the California Current System (Santora et al. 2014; Leising et al. 2015; McClatchie et al. 2016). Years with abundant prey are generally associated with cooler waters, strong upwelling, and higher productivity (Ainley et al. 1993; Becker et al. 2007; Santora et al. 2014; McClatchie et al. 2016), and these conditions may increase murrelet survival and reproductive success (Becker et al. 2007; Vilchis et al. 2015; Vuln. Assessment Reviewer, pers. comm., 2018). By contrast, reduced prey availability likely increases time spent foraging and the distance that seabirds must travel to find sufficient food for themselves and their young (Lorenz et al. 2017; Schneider & Golightly 2018). Prey reductions have caused significant starvation mortality events for other seabirds (Schneider & Golightly 2018; Jones et al. 2018). For instance, extreme anomalies in sea surface temperature caused a large-scale mortality event in Cassin's auklets in 2014–2015, primarily due to shifts in zooplankton composition that effectively reduced energy content within their prey base (Jones et al. 2018).

Sensitivity and current exposure to non-climate stressors

Regional experts evaluated marbled murrelets as having high sensitivity to non-climate stressors (high confidence in evaluation), with an overall moderate-high current exposure to these stressors within the study region (high confidence). Key non-climate stressors that affect marbled murrelets include roads and trails, recreation, timber harvest, and pollution.[5]

<u>Roads/trails and recreation</u>

Human activity in remnant old-growth forest utilized as breeding habitat by marbled murrelets is associated with changes in the distribution and abundance of mammalian and avian species that prey on murrelet eggs and chicks, especially corvids (e.g., ravens, jays; Raphael et al. 2002; Peery & Henry 2010; Goldenberg et al. 2016). Nest predators such as the Steller's jay (*Cyanocitta stelleri*) generally increase as forests become more fragmented because they tend to be associated with edge habitat along roads and are attracted to supplemental food from

[5] All non-climate stressors presented were ranked as having a moderate or higher impact on this species.

recreational visitors around campgrounds and picnic areas (Raphael et al. 2002; Malt & Lank 2007; Goldenberg et al. 2016). Because most remnant old-growth redwood forest in northern California is located in state or national parks, recreational use is prevalent and can impact nest predator populations within a 1 km (0.62 mi) radius of campgrounds and other heavily-used sites (Goldenberg et al. 2016). Thus, the presence of roads and/or recreational activity reduce the likelihood of marbled murrelet nesting and reproductive success across large areas, and have likely contributed to population declines (Raphael et al. 2002; Meyer et al. 2004; Hébert & Golightly 2006, 2007; Golightly et al. 2009; Peery & Henry 2010; Golightly & Schneider 2011). This effect is further compounded by the high levels of fragmentation in remaining old-growth forests, which leave relatively few areas that are unaffected by augmented predator populations (Peery & Henry 2010; Vuln. Assessment Reviewer, pers. comm., 2018).

Timber harvest

Although late-successional forests that are federally owned are protected, logging on private lands is a significant threat to marbled murrelets across their range due to the loss and fragmentation of old-growth coastal forests utilized as nesting habitat (Carter & Erickson 1992; Mendenhall 1992; USFWS 2009; Raphael et al. 2018). In northern California, the remaining breeding habitat is highly fragmented, increasing vulnerability to wildfire and exposing murrelets to higher rates of nest predation (USFWS 1997; Peery et al. 2004; Malt & Lank 2007). Increasing fragmentation as a result of timber harvest can also increase the rate of windthrow at stand edges (Lorimer et al. 2009) and creates overall drier forest conditions (Dawson 1998), potentially altering epiphyte growth and composition and enhancing fire risk (Olson et al. 1990; Glavich et al. 2005).

Pollution

Marbled murrelets are vulnerable to oil spills (Carter & Erickson 1992; Mendenhall 1992), as are most seabirds that utilize diving as a primary foraging strategy (Vilchis et al. 2015). Murrelets are likely also more vulnerable to oil spills because of their reliance on nearshore foraging areas where the risk of a spill event is higher and oil is less likely to disperse in the event that a spill does occur (Vuln. Assessment Reviewer, pers. comm., 2019). Marbled murrelets have been found dead following many oil spills in central and northern California over the past several decades, including the Kurre and Styvessant spills in northern California, and the Command, Luckenbach, Apex Houston, Cosco Bouson, and Pt Reyes tarball spill events in central California (Vuln. Assessment Reviewer, pers. comm., 2018). Chronic low-level oil pollution from bilge pumping and small spills can also cause mortality (Carter & Erickson 1992), and likely are an issue across the region (Vilchis et al. 2015).

Adaptive Capacity

Marbled murrelets were evaluated by regional experts as having moderate overall adaptive capacity (high confidence in evaluation).

Species extent, status, connectivity, and dispersal ability

Regional experts evaluated marbled murrelets as having a moderate geographic extent (high confidence in evaluation), threatened/endangered population status (high confidence), and a moderate-high degree of connectivity between populations (high confidence).

Regional experts evaluated marbled murrelets as having a high dispersal ability (high confidence in evaluation). Barriers to dispersal were evaluated as having a moderate impact on the species (high confidence). Behavioral traits (e.g., extreme site fidelity) was identified as the primary barrier to dispersal.[6]

Marbled murrelets occur across a broad geographic range that encompasses mature and old-growth Pacific coastal forests (Carter & Erickson 1992; Mendenhall 1992; Raphael et al. 2018). In northern California, most remaining marbled murrelet nesting habitat is concentrated in federal and state parks and preserves (Golightly et al. 2009; Falxa & Raphael 2016). Some small remnant old-growth stands are also located on privately-owned timberland in the region (Arcata Fish and Wildlife Office 2018). Over the past century, marbled murrelet nesting habitat has declined by over 80% due primarily to the logging of mature and old-growth forests, which resulted in the listing of this species as federally threatened under the Endangered Species Act in 1992 (USFWS 1992, 1997). Marbled murrelets are also state-listed as endangered in California (California Fish and Game Commission 1992).

The loss and fragmentation of nesting habitat, together with low recruitment rates and at-sea mortality, has likely contributed to population declines observed across the species range (USFWS 1997; Falxa & Raphael 2016; Raphael et al. 2018). Population monitoring efforts focused on the marbled murrelet have found the clearest evidence of declines in Washington (Lynch et al. 2016). Within California, there is some indication that populations have stabilized or increased modestly since implementation of the Northwest Forest Plan in 1994 (Lynch et al. 2016). This suggests that the current protections designed to maintain the species are working reasonably well, although the degree of population recovery is unknown (Vuln. Assessment Reviewer, pers. comm., 2018). Additionally, northern California has higher-than-average murrelet abundance (compared to mean regional abundance across their entire range; Raphael et al. 2015). This, along with aforementioned indicators of possible population increases in northern California (Lynch et al. 2016), suggest that this region may represent an important stronghold for the species (Vuln. Assessment Reviewer, pers. comm., 2018).

Studies suggest that marbled murrelets can travel very long distances (up to 750 km [466 mi]) up and down the coast in years when breeding is not initiated (Adrean et al. 2018), which may represent a search for mates and/or suitable nest sites (Hébert & Golightly 2008). During the non-breeding season, murrelets can remain in the area (Carter & Erickson 1992) and have been observed visiting their nesting habitat, though the reason for this behavior is unknown (Naslund 1993). Long-distance travel is more likely after a failed nest attempt, during the non-breeding

[6] Barriers presented are those ranked as having a moderate or higher impact on this species; additional barriers that may limit habitat continuity and dispersal to a lesser degree include timber harvest.

season, and in non-breeding years (Hébert & Golightly 2008; Peery et al. 2009; Adrean et al. 2018).

Despite the potential for long-distance movement, marbled murrelets typically do not disperse very far inland for nesting (17.7–35.4 km [11–22 miles]), making conservation of coastal old-growth habitat critical (USFWS 1992). Strong site fidelity also increases the potential for breeding disruption as a result of degradation or loss of nesting habitat (De Santo & Nelson 1995; Vuln. Assessment Reviewer, pers. comm., 2018).

Intraspecific/life history diversity

Regional experts evaluated marbled murrelets as having low life history diversity (high confidence in evaluation), moderate-high genetic diversity (low confidence), low-moderate behavioral plasticity (low confidence), and low phenotypic plasticity (high confidence).

Like most seabirds, marbled murrelets are adapted to variable marine environments (USFWS 2009), with the ability to adjust foraging efforts in response to changes in the timing and strength of upwelling as well as changing needs during the nesting period (Hébert & Golightly 2008; Peery et al. 2009). A study of marbled murrelets in central California found that breeding birds increased the amount of time they spent diving by over 70%, diving more frequently in order to meet reproductive demands while nesting (Peery et al. 2009). Breeding birds also forage closer to the nest site and within a smaller range, likely in order to reduce energy expenditure by minimizing the distance between nesting sites and foraging grounds (Hébert & Golightly 2008; Peery et al. 2009).

Marbled murrelets are unique among seabirds in that they travel inland to reproduce (De Santo & Nelson 1995), and in northern California they have limited ability to nest outside of mature or old-growth coastal forests (Golightly et al. 2009). Additionally, marbled murrelets exhibit significant site fidelity, such that individuals are unlikely to abandon a site that becomes unsuitable and renest (Golightly & Schneider 2009; USFWS 2009). This lack of flexibility, combined with the loss of a significant proportion of their nesting habitat, increases the vulnerability of marbled murrelets to population declines (De Santo & Nelson 1995; USFWS 2009). The loss of nesting habitat may also limit the ability of this species to respond to shifts in prey availability near their nesting site (USFWS 2009).

Although marbled murrelet nest predation rates result in frequent nesting failure (Raphael et al. 2002), marbled murrelets have adapted several characteristics that reduce the risk of detection, including effective camouflage and secretive behavior (De Santo & Nelson 1995). For instance, murrelets are primarily active around their nests when the light is low at dawn and dusk (De Santo & Nelson 1995). While incubating, they only switch off every 24 hours and they stay completely motionless for over 98% of the time while on their nest (De Santo & Nelson 1995; Golightly & Schneider 2009).

Resistance and recovery

Regional experts evaluated marbled murrelets as having low resistance to climate stressors and natural disturbance regimes (low confidence in evaluation). Population recovery potential (i.e., recruitment rate) was evaluated as low (low confidence).

Because marbled murrelets have a limited ability to nest outside of old-growth coastal forests, they have low resistance to further loss or fragmentation of nesting habitat, such as might occur during large, uncharacteristically severe fires (USFWS 2009; Raphael et al. 2018).

The average length of time to reproductive maturity in marbled murrelets is 2–4 years (De Santo & Nelson 1995), and their life expectancy is believed to be 10–15 years (Vuln. Assessment Reviewer, pers. comm., 2019). Marbled murrelet clutches are usually just a single egg, which is laid directly on a nesting platform comprised of moss, ferns, or other epiphytes (Hamer & Nelson 1995). Breeding season lasts from roughly mid-April to mid-September, and California populations have been observed to breed earlier than those farther to the north (Carter & Erickson 1992). However, marbled murrelets do not breed every year, further reducing their reproductive rate and increasing vulnerability to population declines (De Santo & Nelson 1995; USFWS 1997). Additionally, they exhibit very strong site fidelity, returning to the same site (and even the same branch) year after year (Golightly & Schneider 2009), which is characteristic of most alcids (Parker et al. 2007). However, recolonization of breeding habitat following extirpation of local populations rarely occurs in alcids (Parker et al. 2007; Vuln. Assessment Reviewer, pers. comm., 2018).

Management potential

Public and societal value

Regional experts evaluated marbled murrelets as having moderate-high public and societal value (high confidence in evaluation).

Marbled murrelets and other seabirds are not necessarily well-known by the general public. However, birders and other special interest groups are generally strong supporters of conservation activities for this species. Some people also view marbled murrelets as a surrogate species representing all old-growth forests in the region. Currently, most conservation groups are aware of murrelets as a conservation issue, and in general the courts have sided with these groups when tested (Vuln. Assessment Reviewer, pers. comm., 2018).

Over the past three decades, considerable societal investments in marbled murrelet conservation have occurred (Raphael et al. 2018; Vuln. Assessment Reviewer, pers. comm., 2018). This includes listing as a threatened species under the federal Endangered Species Act in 1992, which provided significant legal protection (USFWS 1992), followed by the creation and implementation of the Northwest Forest Plan (NWFP) in 1994 (Raphael et al. 2018). Under the NWFP, marbled murrelets are considered a flagship species; thus, protection of nesting habitat is heavily factored into forest management across the Pacific Northwest, including northern California (Raphael et al. 2018). A high proportion of nesting habitat believed to occur on federal land is protected within late-successional reserves (Raphael et al. 2018). Outside of those reserves, murrelet surveys are required before timber harvest occurs on federal lands within the species' range; detection of likely breeding activity results in the protection of all contiguous nesting habitat within a 0.8 km (0.5 mi) radius (Raphael et al. 2018). Many privately-owned old-growth stands are also protected under Habitat Conservation Plans or Safe Harbor Agreements (Arcata Fish and Wildlife Office 2018).

Management capacity and ability to alleviate impacts[7]

Regional experts evaluated the potential for reducing climate impacts on marbled murrelets through management as low-moderate (high confidence in evaluation).

Most management strategies for marbled murrelets focus on maintaining and, eventually, increasing nesting habitat in order to support regional murrelet populations (Raphael et al. 2018). Protection efforts could consider the combined effects of climate change and habitat fragmentation by focusing on areas where projected climate conditions are expected to remain within or close to the suitable range for coast redwood (DellaSala et al. 2018). The creation of large reserves is the most effective way to minimize the edge effect in murrelet nesting habitat patches; where that is not possible, smaller old-growth stands can be surrounded with regenerating forest to reduce the predation risk associated with hard edges (Malt & Lank 2007). Existing old-growth forests that provide high-quality nesting habitat include cool, moist low-elevation stands of old-growth forest with large trees, especially those adjacent to streams (Meyer et al. 2004; Golightly et al. 2009). Protecting and enhancing nesting habitat close to the coast could minimize the distance traveled for foraging (Lorenz et al. 2017), while prioritizing areas far away from roads and other sources of anthropogenic disturbances is likely to minimize the risk of nest predation and other negative impacts associated with roads and recreational areas (Meyer et al. 2004; Golightly et al. 2009).

Other management options include the protection and enhancement of regenerating redwood forests that represent potential nesting habitat (USFWS 2009; Raphael et al. 2018). In these areas, management strategies can accelerate the development of characteristics that reflect the forest composition and structure of old-growth forest and potentially increase resilience to future climate changes (DellaSala et al. 2018; Sillett et al. 2018). For instance, restoration tools such as variable density thinning in dense second-growth stands can encourage redwood growth, increase structural diversity, and shift species composition towards enhanced dominance of redwoods (van Mantgem & Das 2014; Dagley et al. 2018). After thinning, crown manipulation in young forests (e.g., strategic tree injury) can initiate trunk reiteration and limb formation within the crown, increasing structural complexity (Sillett et al. 2018).

Another important management strategy that may aid the recovery of marbled murrelet populations in California includes reducing corvid nest predation (Peery & Henry 2010). This primarily occurs through limiting anthropogenic activity (e.g., traffic, recreation) in old-growth

[7] Further information on climate adaptation strategies and actions for northern California can be found on the project page (https://bit.ly/31AUGs5).

forest, as well as managing food scraps and garbage in campgrounds and picnic areas (Golightly et al. 2009). The impacts of recreation in Redwood National and State Parks are currently being addressed through strategies such as public education campaigns that emphasize not providing food for jays and ravens (Vuln. Assessment Reviewer, pers. comm., 2018).

Managers have little ability to enhance marine foraging habitat if prey availability decreases, but some strategies could reduce the potential for anthropogenic impacts on marbled murrelets in the marine environment (Vuln. Assessment Reviewer, pers. comm., 2018). For instance, increased use of alternative energy sources could reduce the likelihood of oil spills and the corresponding negative impacts on seabird populations by limiting the transport of oil over water (Vuln. Assessment Reviewer, pers. comm., 2018). Protection efforts for marine areas should prioritize those that are close to large reserves of nesting habitat and have a low human footprint (Lorenz et al. 2016).

Ecosystem services

Marbled murrelets primarily provide cultural ecosystem services, including knowledge systems, educational values, aesthetic values, sense of place, inspiration, and recreation (Vuln. Assessment Reviewer, pers. comm., 2018). They are likely also responsible for a modest amount of nutrient transfer from marine to forest habitats (Vuln. Assessment Reviewer, pers. comm., 2018).

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Further information on the Northern California Climate Adaptation Project is available on the project website (https://tinyurl.com/NorCalAdaptation).

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Northern California Climate Adaptation Project:

Vulnerability Assessment Methods and Application

Defining Terms

Exposure: A measure of how much of a change in climate or climate-driven factors a resource is likely to experience (Glick et al. 2011).

Sensitivity: A measure of whether and how a resource is likely to be affected by a given change in climate or factors driven by climate (Glick et al. 2011).

Adaptive Capacity: The ability of a resource to accommodate or cope with climate change impacts with minimal disruption (Glick et al. 2011).

Vulnerability: A function of the sensitivity of a particular resource to climate changes, its exposure to those changes, and its capacity to adapt to those changes (IPCC 2007).

Vulnerability Assessment Model

The vulnerability assessment model applied in this process was developed by EcoAdapt (EcoAdapt 2014a; EcoAdapt 2014b; Kershner 2014; Hutto et al. 2015; Gregg 2018),[8] and includes evaluations of relative vulnerability by local and regional stakeholders who have detailed knowledge about and/or expertise in the ecology, management, and threats to focal habitats, species groups, individual species, and the ecosystem services that these resources provide. Stakeholders evaluated vulnerability for each resource by discussing and answering a series of questions for sensitivity and adaptive capacity. Exposure was evaluated by EcoAdapt using projected future climate changes from the scientific literature. Each vulnerability component (i.e., sensitivity, adaptive capacity, and exposure) was divided into specific elements. For example, habitats included three elements for assessing sensitivity and six elements for adaptive capacity. Elements for each vulnerability component are described in more detail below.

In-person workshops were held in Eureka, Redding, and Upper Lake between May and October 2017. Participants self-selected habitat and species group/species breakout groups and evaluated the vulnerability of each resource. Participants were first asked to describe the habitat and/or to list the species to be considered in the evaluation of an overarching species group. Due to limitations in workshop time and participant expertise, multiple resources were not assessed during these engagements. Evaluations for remaining habitats, species groups, and species were completed by contacting resource experts.[9]

[8] Sensitivity and adaptive capacity elements were informed by Lawler 2010, Glick et al. 2011, and Manomet Center for Conservation Sciences 2012.

[9] Resources evaluated by experts included: coastal bluff/scrub habitats, coastal conifer hardwood forest, true fir forest, lakes/ponds, freshwater marshes, vernal pools, seeps/springs, native insect pollinators, native ungulates, salamanders, frogs, native mussels, marbled murrelet, and northwestern pond turtle.

Stakeholders assigned one of five rankings (High, Moderate-High, Moderate, Low-Moderate, or Low) for sensitivity and adaptive capacity. EcoAdapt assigned rankings for projected future climate exposure. Rankings for each component were then converted into scores (High-5, Moderate-High-4, Moderate-3, Low-Moderate-2, or Low-1), and the scores were averaged (mean) to generate an overall score. For example, scores for each element of habitat sensitivity were averaged to generate an overall habitat sensitivity score. Scores for exposure were weighted less than scores for sensitivity and adaptive capacity because the uncertainty about the magnitude and rate of future change is greater. Sensitivity, adaptive capacity, and exposure scores were combined into an overall vulnerability score calculated as:

Vulnerability = [(Climate Exposure*0.5) x Sensitivity] - Adaptive Capacity

Elements for each component of vulnerability were also assigned one of three confidence rankings (High, Moderate, or Low). Confidence rankings were converted into scores (High-3, Moderate-2, or Low-1) and the scores averaged (mean) to generate an overall confidence score. These approximate confidence levels were based on the Manomet Center for Conservation Sciences (2012) 3-category scale, which collapsed the 5-category scale developed by Moss and Schneider (2000) for the IPCC Third Assessment Report. The vulnerability assessment model applied here assesses the confidence associated with individual element rankings and, from these rankings, estimates the overall level of confidence for each component of vulnerability and then for overall vulnerability.

Stakeholders and decision-makers can consider the rankings and scores presented as measures of relative vulnerability and confidence to compare the level of vulnerability among the focal resources evaluated in this project. Elements that received lower confidence rankings indicate knowledge gaps that applied scientific research could help address.

Vulnerability Assessment Model Elements

Sensitivity & Exposure (Applies to Habitats, Species Groups, Species)

- **Climate and Climate-Driven Factors:** e.g., air temperature, precipitation, freshwater temperature, soil moisture, snowpack, extreme events: drought, altered streamflows, etc.
- **Disturbance Regimes:** e.g., wildfire, flooding, drought, insect and disease outbreaks, wind
- **Future Climate Exposure:** e.g., consideration of projected future climate changes (e.g., temperature and precipitation) as well as climate-driven changes (e.g., altered fire regimes, altered water flow regimes, shifts in vegetation types)
- **Stressors Not Related to Climate:** e.g., tectonic and volcanic events; residential or commercial development; agriculture and/or aquaculture; roads, highways, trails; dams and water diversions; invasive and other problematic species; livestock grazing; fire suppression; timber harvest; mining; etc.

Sensitivity & Exposure (Applies to Species Groups and Species)

- **Dependencies:** e.g., dependencies on sensitive habitats, specific prey or forage species, and the timing of the appearance of these prey and forage species (concern for mismatch)

Sensitivity & Exposure (Applies to Species ONLY)

- **Life History:** e.g., species reproductive strategy, average length of time to reproductive maturity

Adaptive Capacity (Applies to Habitats, Species Groups, Species)

- **Extent, Integrity, and Continuity/Connectivity:** e.g., resources that are widespread vs. limited, structural and functional integrity (e.g., degraded or pristine) of a habitat or health and functional integrity of species (e.g., endangered), isolated vs. continuous distribution
- **Landscape Permeability:** e.g., barriers to dispersal and/or continuity (e.g., land-use conversion, energy production, roads, timber harvest, etc.)
- **Resistance and Recovery:** e.g., *resistance* refers to the stasis of a resource in the face of change, *recovery* refers to the ability to "bounce back" more quickly from the impact of stressors once they occur
- **Management Potential:** e.g., ability to alter the adaptive capacity and resilience of a resource to climatic and non-climate stressors (societal value, ability to alleviate impacts, capacity to cope with impacts)
- **Ecosystem Services:** e.g., provisioning, regulating, supporting, and/or cultural services that a resource produces for human well-being

Adaptive Capacity (Applies to Habitats ONLY)

- **Habitat Diversity:** e.g., diversity of physical/topographical characteristics, component native species and functional groups

Adaptive Capacity (Applies to Species Groups, Species)

- **Dispersal Ability**: i.e., ability of a species to shift its distribution across the landscape as the climate changes
- **Intraspecific/Life History Diversity:** e.g., life history diversity, genetic diversity, phenotypic and behavioral plasticity

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