



Migratory Birds

Northern California Climate Change Vulnerability Assessment Synthesis

An Important Note About this Document: This document represents an initial evaluation of vulnerability for migratory birds 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 reviewers for this document included Anonymous (Klamath Bird Observatory), Jeffrey Black (Humboldt State University), Jesse Irwin (Bureau of Land Management), and Nathaniel Seavy (Point Blue Conservation Science). Vulnerability scores were provided by Eureka and Redding workshop participants. Upper Lake workshop participants provided additional comments on the climate change vulnerability of this species group.

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Species Group Description

Migratory birds are characterized by their seasonal travel from breeding to wintering grounds, distances that range from a few hundred up to thousands of kilometers (Henningsson & Alerstam 2005; Berlanga et al. 2010; NABCI 2016). Migration allows birds to track the availability of resources such as food and nesting sites, and most North American species

migrate from breeding grounds in the north to wintering grounds in the southern part of their range (Henningsson & Alerstam 2005; Berlanga et al. 2010). However, some short-distance migrants move along elevational gradients (Tingley et al. 2012; Wiegardt et al. 2017), and a recent study found that more than half the species studied in the western United States are “altitudinal” or short-distance migrants within the region, including species in virtually every bird family in California (Boyle 2017). The timing of seasonal migration and breeding behavior is tied to interacting factors such as photoperiod (Dawson et al. 2001; Cornelius & Hahn 2012), temperature (Miller-Rushing et al. 2008), and resource availability (Henningsson & Alerstam 2005; Studds & Marra 2011). Northern California lies within the Pacific Flyway, a 6,400 km (4,000 mi) route utilized by millions of birds every year (Page et al. 1999; NAWMP 2012). This assessment will focus on the following key functional groups:

- Shorebirds (e.g., sandpipers, plovers, terns): Many shorebirds migrate long distances between their breeding and wintering grounds (Page et al. 1999; Henningsson & Alerstam 2005; Galbraith et al. 2014; NABCI 2016). Humboldt Bay represents an important habitat area for migrating and wintering shorebirds that breed in the arctic and subarctic regions of Alaska and Canada, such as the Black-bellied Plover (*Pluvialis squatarola*), Western Sandpiper (*Calidris mauri*), Least Sandpiper (*C. minutilla*), and Dunlin (*C. alpina*; Page et al. 1999; Hickey et al. 2003; Colwell & Feucht 2018). By contrast, the Western Snowy Plover (*Charadrius nivosus nivosus*) is a short-distance migrant that moves north or south along the coast (Page et al. 2009). Migrating and wintering shorebirds use intertidal mudflats, beaches, wetlands, and agricultural fields for foraging and roosting (Colwell & Dodd 1997; Colwell & Sundeen 2000; Long & Ralph 2001; Hickey et al. 2003; Stralberg et al. 2010). Breeding shorebirds primarily utilize beaches, dunes, and shallow-flooded wetlands as nesting habitat (Hickey et al. 2003; Strum et al. 2017).
- Waterfowl (e.g., ducks, geese): Waterfowl utilize freshwater wetlands, estuaries, and agricultural areas for nesting, foraging, and roosting, as well as bays, lakes, and other areas of open water (Fleskes & Yee 2007; Stralberg et al. 2010). Breeding ducks also use adjacent upland areas for nesting (Ackerman et al. 2011). Species that winter in California often breed in arctic and subarctic areas or in the prairie pothole region in the upper Midwest (NAWMP 2012; NABCI 2016). Many birds winter in and around Humboldt Bay (Moore et al. 2004), and stopover sites in the region are also used by a large proportion of the waterfowl that use the Pacific Flyway, including the Northern Pintail (*Anas acuta*), Pacific Brant (*Branta bernicla nigricans*), and Aleutian Cackling Goose (*Branta hutchinsii leucopareia*; Black et al. 2004; Moore et al. 2004; Fleskes & Yee 2007).
- Songbirds (e.g., finches, warblers, sparrows, etc.): Migratory songbirds occupy the full range of inland habitats across the region, including shrublands (Jennings 2018), oak woodlands (CalPIF 2002a; Altman & Stephens 2012), conifer and hardwood forests (Raphael 1991; CalPIF 2002b), and riparian areas (DiGaudio et al. 2015). These species occupy a wide variety of niches, with nest site preferences, foraging guild, and migration strategy varying by species (Berlanga et al. 2010; NABCI 2016). Many migratory songbirds are Neotropical migrants that winter in Mexico and Central and South America, though a few species migrate shorter distances or primarily move along

elevational gradients (Berlanga et al. 2010; McGrann & Furnas 2016; NABCI 2016). Additionally, irruptive species, such as the Red Crossbill (*Loxia curvirostra*) migrate in irregular patterns driven largely by variable conifer seed production (Adkisson 1996).

Executive Summary

The relative vulnerability of migratory birds in northern California was evaluated as moderate by regional experts due to moderate-high (for waterfowl/ songbirds) or moderate (for shorebirds) sensitivity to climate and non-climate stressors, moderate exposure to projected future climate changes, and high adaptive capacity.

Rank (Confidence)	Shorebirds	Waterfowl & Songbirds
Sensitivity	Moderate (High)	Moderate-High (High)
Exposure	Moderate (Moderate)	Moderate (Moderate)
Adaptive Capacity	High (High)	High (High)
Collective Vulnerability	Moderate (High)	Moderate (High)

Sensitivity & Exposure Summary	<p><u>Climate and climate-driven factors:</u></p> <ul style="list-style-type: none"> Precipitation amount, drought, sea level rise, water temperature, heat waves, streamflow <p><u>Disturbance regimes:</u></p> <ul style="list-style-type: none"> Wildfire, insects, disease <p><u>Non-climate stressors:</u></p> <ul style="list-style-type: none"> Land-use conversion (for residential/commercial development, agriculture, and energy), fire exclusion and suppression, recreation, pollution (e.g., oil spills, pesticide, livestock grazing, hunting)
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Migratory birds are likely to be impacted by climate stressors and changes in disturbance regimes that increase physiological stress and/or cause mortality (e.g., heat waves, disease), as well as changes in precipitation and drought that may reduce habitat availability and contribute to phenological mismatches between insect emergence and the timing of avian migration and breeding. Factors that impact moisture availability (e.g., precipitation, drought) or alter disturbance regimes in upland areas (e.g., changes in streamflow, insect outbreaks) may also change the structure and composition of habitats, potentially reducing their suitability for nesting and foraging. Sea level rise will cause inundation and erosion in coastal areas, while severe drought can result in the drying of wetlands, leading to habitat loss for many shorebirds and waterfowl. Key non-climate stressors for migratory birds include land-use conversion (for residential/commercial development, agriculture, and energy development), fire suppression, recreation, pollution, livestock grazing, and hunting. These factors impact migratory birds directly by increasing nest predation and adult mortality, and indirectly by altering habitat and/or food source availability and quality.

Adaptive Capacity Summary	<p><u>Factors that enhance adaptive capacity:</u></p> <ul style="list-style-type: none"> + Represents wide variety of families, foraging guilds, and life history strategies + Some species able to shift migration timing and/or route, nest site selection, and foraging strategy in response to climate conditions and habitat loss + Highly mobile <p><u>Factors that undermine adaptive capacity:</u></p> <ul style="list-style-type: none"> – Population declines in many species, due in part to habitat loss and fragmentation – Additional challenge of managing disparate breeding and wintering habitats as well as migratory stopover sites
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Migratory birds have already been significantly impacted by habitat loss and fragmentation, contributing to population declines in many species. However, this species group exhibits a wide variety of life history strategies, and species with high genetic diversity or behavioral flexibility have demonstrated the ability to shift migration timing and/or route, nest site location, and foraging strategy in response to changing climate conditions and habitat loss. Resistance to climate stressors and disturbance regimes is supported by the high mobility of this species group. Migratory birds receive high public and societal support, although management of breeding and wintering habitats across geopolitical boundaries can pose a challenge. The scientific literature suggests a number of strategies that could increase the resilience of migratory birds to climate change, which include increasing habitat availability and connectivity, reducing nest predation and brood parasitism, restoring natural disturbance regimes such as fire and flooding, and protecting potential climate refugia (e.g., riparian corridors, old-growth forest).

Sensitivity and Exposure

Waterfowl and songbirds were evaluated by regional experts as having moderate-high overall sensitivity (high confidence in evaluation) to climate and climate-driven factors, changes in disturbance regimes, and non-climate stressors, while shorebirds were evaluated as having moderate overall sensitivity (high confidence). All groups were evaluated as having moderate overall future exposure (high confidence).

Warmer, drier conditions over the coming century are likely to contribute to changes in the location and/or size of breeding and wintering ranges in most migratory birds (Stralberg et al. 2009; National Audubon Society 2013; Veloz et al. 2013; Galbraith et al. 2014; Langham et al. 2015). Range shifts are likely as warm-adapted bird species extend their range boundaries into formerly colder regions (VanDerWal et al. 2013; Princé & Zuckerberg 2015), which, for some species, is projected to result in northwards shifts in response to increasingly unsuitable climatic conditions within their current ranges (NABCI 2010;

Potential Changes in Species Group Distribution
<ul style="list-style-type: none"> • Changes in community composition due to heterogeneous range shifts in individual species (likely to result in novel communities) • Northward shifts in distribution will likely occur for many species
<p>Source(s): Stralberg et al. 2009; National Audubon Society 2013; Veloz et al. 2013; Langham et al. 2015</p>

National Audubon Society 2013; Langham et al. 2015). However, projections of elevational and latitudinal range shifts are heterogeneous among species (Tingley et al. 2012; Langham et al. 2015).

Because individual species ranges shift independently in response to a combination of climate variables (e.g., temperature, precipitation), avian community composition will likely change (Stralberg et al. 2009). By 2070, novel community assemblages may occur across 10-57% of the state's land area, potentially altering ecological dynamics such as predator/prey interactions and interspecific competition for resources such as food and nesting sites (Stralberg et al. 2009). In northern California, the most significant changes in species composition are projected to occur in the southwestern foothills of the Cascades (along the northern edge of the Sacramento Valley) and, to a lesser degree, within the North Coast region (Stralberg et al. 2009).

For montane songbirds, studies suggest that complex, middle-elevation forests may provide a refugia for both long-distance and altitudinal migrants (Tingley & Beissinger 2013; McGrann & Furnas 2016). Dense, closed-canopy stands of mature and old-growth forest, in particular, may provide important microrefugia that protect migratory songbirds from thermal stress (Frey et al. 2016). Riparian ecosystems are also generally considered more resilient to climate change than surrounding upland areas (Seavy et al. 2009; Capon et al. 2013). For instance, these areas are likely to buffer the impacts of higher temperatures and reduced water availability under future climate conditions, and are also adapted to recover rapidly from disturbances such as flooding (Seavy et al. 2009). Thus, birds may be less likely to experience extreme climatic changes (Gardali et al. 2012; DiGaudio et al. 2015).

Site-specific conditions such as high shoreline accretion rates paired with higher initial elevation may buffer exposure to sea level rise for shorebirds and waterfowl in some areas (Thorne et al. 2018). The presence of flood-tolerant vegetation such as California cordgrass (*Spartina foliosa*) also may reduce the vulnerability of specific sites to inundation (Thorne et al. 2018). However, in northern California this species is concentrated in the tidal wetlands of Humboldt Bay (Calflora 2019), where sea level rise is expected to occur more rapidly than the rest of the region (NHE 2015; Patton et al. 2017; Laird 2018).

Sensitivity and future exposure to climate and climate-driven factors

Regional experts evaluated waterfowl as having high sensitivity to climate and climate-driven factors (high confidence in evaluation) with an overall moderate-high future exposure to these factors within the study region (low confidence). Songbirds were evaluated as having moderate-high sensitivity (high confidence) and moderate-high future exposure (low confidence), while shorebirds were evaluated as having moderate-high sensitivity (high confidence) and moderate future exposure (low confidence). Key climatic factors that affect

migratory birds include precipitation amount, drought, sea level rise, water temperature, heat waves, and streamflow.¹

Precipitation amount and drought

Changes in amounts of precipitation and increased periods of drought are likely to impact migratory birds in tidal wetlands and freshwater wetlands differently. In freshwater wetlands, winter rainfall or managed water deliveries influence habitat availability and quality (Ackerman et al. 2011; Reiter et al. 2018). Drier conditions, in particular, may cause declines in the extent of freshwater wetlands and other flooded areas (e.g., croplands) used by waterfowl and non-breeding shorebirds (Ackerman et al. 2011; Reiter et al. 2015, 2018; Schaffer-Smith et al. 2017), groups that are already limited by lack of habitat availability and food resources in the northern Sacramento Valley during the fall migration (Dybala et al. 2017; Golet et al. 2018). During severe multi-year droughts, open water habitat in the Sacramento Valley (e.g., ponds, wetlands, flooded cropland) can decrease by up to 69% (Reiter et al. 2018). By contrast, increases in the amount of winter precipitation could enhance freshwater habitat availability and quality for wintering and migratory waterfowl and shorebirds (Ackerman et al. 2011).

In northern California, coastal estuaries are often located at the mouths of major rivers and are characterized by brackish conditions due to their tidal influence (Colwell 1993; Vuln. Assessment Reviewer, pers. comm., 2018). Although habitat availability in coastal wetlands primarily depends on seasonal tidal patterns (Colwell 1993), conditions are also influenced by annual precipitation (Colwell 1993; Stenzel & Page 2018). For instance, heavy precipitation is associated with decreased abundance for many shorebirds and waterfowl (Stenzel & Page 2018), likely the direct result of declines in habitat availability and quality at critical migration peaks (Colwell 1993). During periods of drought, coastal estuaries generally maintain their habitat value to a greater degree compared to freshwater wetlands (Colwell 1993; Vuln. Assessment Reviewer, pers. comm., 2018).

Reduced vegetation productivity as a result of drought may also result in a loss of food resources (e.g., seeds, berries, insects) and cover, particularly for songbirds (Chase et al. 2005; Bolger et al. 2005; Albright et al. 2010; Ackerman et al. 2011; Ferger et al. 2014). Drought has been associated with changes in the abundance, richness, and composition of songbird communities, with the most significant changes noted in long-distance migrants (Albright et al. 2010). Seed-eating birds, such as Pine Siskins (*Spinus pinus*) and Red Crossbills, are particularly vulnerable to declines in plant productivity (e.g., cone crops) as a result of dry conditions (Vuln. Assessment Workshop, pers. comm., 2017). The relationship between precipitation amount and avian productivity is particularly strong in dry areas, and total reproductive failure can occur in shrubland species during severe drought years (Bolger et al. 2005). Thus, increases in the frequency of drought have the potential to result in population declines, particularly if the

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

number of wet years associated with high reproductive success also decreases (Bolger et al. 2005).

Regional Precipitation & Drought Trends²	
<p><i>Historical & current trends:</i></p> <ul style="list-style-type: none"> • 2.6–9.4 cm (1.0–3.7 in) increase in mean annual precipitation between 1900 and 2009 for the Northwestern California, Southern Cascade, and Great Valley ecoregions (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) 	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> • 23% decrease to 38% increase in mean annual precipitation by 2100 (compared to 1951–1980) for the North Coast, Northern Coast Range, Northern Interior Coast Range, Klamath Mountain, Southern Cascade, and Great Valley ecoregions (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 Group (see text for citations)	
<ul style="list-style-type: none"> • Reduced habitat availability and food resources for waterfowl and non-breeding shorebirds • Reduced food availability due to decreases in plant and insect productivity, potentially resulting in reduced reproductive success, changes in community composition, and population declines 	

² Trends in climate factors and natural disturbance regimes presented in this and subsequent summary tables are not species group-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.

³ Projections for changes in annual and seasonal precipitation by ecoregion can be found in the full climate impacts table (<https://bit.ly/2LHgZaG>).

Sea level rise

Over the coming decades, sea level rise is likely to cause increased erosion and inundation of coastal beaches, dunes, estuaries, and intertidal mudflats used by migratory shorebirds and waterfowl (Galbraith et al. 2002, 2014; Thorne et al. 2018). The impacts of sea level rise will vary along the northern California coast based on relative sea level rise rates, site geology and exposure to erosion, extent of coastal armoring, and development that prevents landward migration of dune systems, among other factors (Heady et al. 2018; Laird 2018; Ocean Protection Council 2018). For instance, landward migration of coastal dunes and wetlands can occur in areas with adequate sediment deposition and little or no development on the inland edge (Vitousek et al. 2017; Heady et al. 2018). However, urban encroachment or steep terrain limits this potential along much of the northern California coast (Thorne et al. 2018). In the Humboldt Bay region, land subsidence has increased rates of sea level rise compared to the rest of the Pacific Coast (NHE 2015; Patton et al. 2017; Laird 2018). As a result, breeding, wintering, and migrating shorebirds and waterfowl are expected to experience severe habitat loss in and around Humboldt Bay, potentially resulting in reduced abundance and/or population declines (Galbraith et al. 2002). Along migration stopover routes, habitat loss at bottleneck points (i.e., points through which a large proportion of the population of bird species passes) could also have a disproportionate effect on some species (Iwamura et al. 2013).

Regional Sea Level Rise Trends	
<p><i>Historical & current trends:</i></p> <ul style="list-style-type: none"> • At the Crescent City station, sea levels decreased by an average of 0.08 cm (0.03 in) per year from 1933–2018 (equivalent to a decrease of 0.08 m [0.26 ft] in 100 years; NOAA/National Ocean Service 2019) • At the Humboldt Bay (North Spit) station, sea levels increased by an average of 0.49 cm (0.19 in) per year from 1977–2018 (equivalent to an increase of 0.49 m [1.6 ft] in 100 years; NOAA/National Ocean Service 2019) • At the Arena Cove station, sea levels increased by an average of 0.08 cm (0.03 in) per year from 1978–2018 (equivalent to a change of 0.08 m [0.27 ft] in 100 years; NOAA/National Ocean Service 2019) 	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> • Sea level rise trends by 2100 (compared to 2000), based on likelihood of occurrence (range includes projections linked to low-, moderate-, and high-emissions scenarios; Kopp et al. 2014; Griggs et al. 2017; Sweet et al. 2017; Anderson 2018): <ul style="list-style-type: none"> ○ For the Crescent City station, 66% probability of 0.03–0.65 m (0.1–2.1 ft), 0.5% probability of 1.25–1.55 m (4.1–5.1 ft), and extreme scenario (representing ice sheet collapse) of 2.79 m (9.1 ft) ○ For the Humboldt Bay (North Spit) station, 66% probability of 0.62–1.24 m (2.0–4.1 ft), 0.5% probability of 1.83 to 2.15 m (6.0–7.0 ft), and extreme scenario (representing ice sheet collapse) of 3.37 m (11.0 ft) ○ For the Arena Cove station, 66% probability of 0.21–0.94 m (0.7–3.1 ft), 0.5% probability of 1.65–2.04 m (5.4–6.7 ft), and extreme scenario (representing ice sheet collapse) of 3.02 m (9.9 ft)
<p>Summary of Potential Impacts on Species Group <i>(see text for citations)</i></p>	
<ul style="list-style-type: none"> • Habitat loss for shorebirds and waterfowl due to increased inundation and erosion in coastal 	

Regional Sea Level Rise Trends

- beaches, dunes, estuaries, and intertidal mudflats
- Reduced bird abundance and potential population declines as a result of the loss of breeding or wintering habitat and migratory stopover sites

Water temperature

Changes in water temperature are likely to alter aquatic food webs, impacting the abundance and phenology of plants, invertebrate, and fish consumed by waterfowl (NABCI 2010). Warmer water temperatures also increase phytoplankton blooms, which can lead to dead zones within estuaries and nearshore coastal habitats (NABCI 2010). Declines in eelgrass as a result of increased water temperatures have contributed to shifts in brant distribution as forage availability decreases (Ward et al. 2005), and are likely to impact shorebirds in Humboldt Bay as well (Vuln. Assessment Reviewer, pers. comm., 2019).

Regional Water & Sea Surface Temperature Trends

Historical & current trends:

- ~0.1°C (0.2°F) per decade increase in mean August stream temperatures in northwestern California from 1976–2015 (Isaak et al. 2017)
 - Corresponds to a 0.4°C (0.7°F) increase in air temperature and 5.3% decrease in discharge per decade
- 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)

Projected future trends:

- 0.4–0.8°C (0.7–1.4°F) per decade increase in mean August stream temperatures in northwestern California by the 2080s (Isaak et al. 2017)
 - Corresponds to a 3.6°C (6.5°F) increase in air temperature and 1.2% decrease in stream discharge
- 1–3°C (1.8–5.4°F) increase in the temperature of the Sacramento River by 2100 (Cloern et al. 2011)
- 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)

Summary of Potential Impacts on Species Group *(see text for citations)*

- Changes in aquatic food webs, impacting forage and prey abundance and phenology
- Reduced water quality due to phytoplankton blooms
- Possible declines and/or shifts in species distribution for species highly dependent on eelgrass

Heat waves

Extreme temperatures can result in nest failure (Ackerman et al. 2011), dehydration, and possible mortality in birds (Albright et al. 2017; Zhang et al. 2017). Thus, changes in the frequency and/or severity of heat waves may reduce survival and reproductive success (Jiguet et al. 2006; Ackerman et al. 2011; Albright et al. 2017). Small songbirds are more vulnerable to heat waves than larger birds because they lose water at a higher rate, increasing the potential for dehydration on hot days when evaporative cooling demands are greater (Albright et al. 2017). A study of montane songbirds in northern California found that Neotropical migrants

were less likely than resident species and altitudinal migrants to reduce vocal activity on hot days during the breeding season, potentially increasing their vulnerability to heat stress given that singing is energetically expensive (McGrann & Furnas 2016). Studies also suggest that species distributed across narrower thermal ranges may be more likely to experience population declines, possibly because they tend to nest and forage within more specialized microenvironments in the landscape (Jiguet et al. 2006). Similarly, populations breeding near the upper limits of the species thermal range exhibit lower rates of growth, regardless of latitude (Jiguet et al. 2010).

Regional Heat Wave Trends	
<p><i>Historical & current trends:</i></p> <ul style="list-style-type: none"> • Increase in the frequency of humid nighttime events over the past several decades (Gershunov & Guirguis 2012) • High interannual and interdecadal variability in heat waves (Gershunov & Guirguis 2012) 	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> • Increased heat waves, with the greatest increase in humid nighttime heat waves and in 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 Group <i>(see text for citations)</i>	
<ul style="list-style-type: none"> • Reduced survival and reproductive success, potentially resulting in population declines for vulnerable species 	

Streamflow

Changes in streamflow volume and the timing of peak flows are likely to affect the productivity, composition, and structure of vegetation in riparian corridors (Bendix & Hupp 2000; Glenn & Nagler 2005; Stromberg et al. 2010; Perry et al. 2012). This, in turn, affects food availability (e.g., insects, seeds) and habitat suitability for migratory songbirds (Herrera & Dudley 2003; RHJV 2004). Lower flows, in particular, may reduce native trees that depend on periodic flooding for dispersal and germination, such as willow (*Salix* spp.) and cottonwood (*Populus* spp.; Glenn & Nagler 2005; Rood et al. 2005; Stella et al. 2006; Perry et al. 2012). In their absence, the establishment of stress-tolerant invasive species (e.g., tamarisk [*Tamarix* spp.]) may increase, especially in the Sacramento Valley foothills, reducing plant diversity and structural complexity (Herrera & Dudley 2003; Glenn & Nagler 2005; Stromberg et al. 2010). High flows as a result of climate-driven increases in heavy winter precipitation events could also damage and kill riparian trees and shrubs (Vuln. Assessment Reviewer, pers. comm., 2019).

Regional Streamflow Trends	
<p><i>Historical & current trends:</i></p> <ul style="list-style-type: none"> • Shift towards earlier spring peak flows in snowmelt-dominated basins (Stewart et al. 2005; Pierce et al. 2018) • In rain-dominated coastal rivers in northern California, minimum annual flows have 	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> • Generally, wet season flows are projected to increase and dry season flows are projected to decrease (Leng et al. 2016; Grantham et al. 2018) • Overall increase in flow variability and earlier

Regional Streamflow Trends	
<p>decreased and late summer recession rates have increased over the past 40-80 years (Sawaske & Freyberg 2014; Asarian & Walker 2016; Klein et al. 2017)</p> <ul style="list-style-type: none"> September streamflow declined at 73% of undammed sites in northern California and southwest Oregon (Asarian & Walker 2016) 	<p>timing of spring peak flows (by up to 30 days; Stewart et al. 2005)</p> <ul style="list-style-type: none"> As a result of more extreme dry conditions, the lowest streamflow per decade is projected to be 30–40% lower by 2100 (Pierce et al. 2018)
Summary of Potential Impacts on Species Group <i>(see text for citations)</i>	
<ul style="list-style-type: none"> Changes in food availability and habitat suitability due to shifts in the productivity, composition, and structure of riparian vegetation 	

Sensitivity and future exposure to changes in natural disturbance regimes

Regional experts evaluated songbirds as having 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 (moderate confidence). Waterfowl were evaluated as having moderate sensitivity (high confidence) and moderate future exposure (moderate confidence), while shorebirds were evaluated as having low sensitivity (high confidence) and moderate future exposure (moderate confidence). Key natural disturbance regimes that affect migratory birds include wildfire, insects, and disease.⁴

Wildfire

Wildfire impacts migratory songbirds by altering habitat structure (e.g., reducing canopy cover, increasing snags) and/or resetting succession in severely burned areas (Fontaine et al. 2009; Hankins 2013; Stephens et al. 2015), as well as more indirectly by causing shifts in food availability and through predator/prey interactions (Alexander et al. 2004). Wildfire regimes in northern California vary widely depending on vegetation, climate, and topography (Agee 1996; Huff et al. 2005; Van de Water & Safford 2011; Perry et al. 2011). Prior to the widespread implementation of fire suppression practices in the early 1900s,⁵ mesic forests in northern California were largely dominated by mixed-severity fire regimes that included irregular patches of low-, moderate-, and high-severity fire, while dry ponderosa/mixed conifer forests and oak woodlands experienced frequent low-intensity fire (Agee 1996; Perry et al. 2011; Skinner et al. 2018; Skinner & Taylor 2018). Chaparral shrublands were typically characterized by higher-intensity crown fires (Keeley & Davis 2007). Fire dynamics in the region changed following Euro-American settlement, and fires in the region now tend to be larger and more dominated by mixed-severity fires (Perry et al. 2011; Halofsky et al. 2011; Hessburg et al. 2016).

⁴ All disturbance regimes presented were ranked as having a moderate or higher impact on this species group within the study region (see “Dependency on habitat and/or other species” section below for discussion of changes in other parts of a species’ range).

⁵ Refer to the section on non-climate stressors for a more complete discussion of the impacts of fire suppression on migratory birds.

Cultural burning has been practiced by tribes across the region for centuries, particularly at lower elevations, and has played a critical role in shaping vegetation structure and composition (Underwood et al. 2003; Mensing 2005; Anderson 2006; Fry & Stephens 2006; Stephens et al. 2007; Skinner et al. 2009; Norgaard et al. 2016; Karuk Tribe 2019). Thus, tribal management of the landscape also benefits the migratory species that depend on these habitat types (Hankins 2013; Norgaard et al. 2016; Karuk Tribe 2019). For instance, frequent low- to moderate-intensity fire in riparian areas maintains open areas with the early-successional trees and shrubs (e.g., willow, cottonwood) on which many migratory species depend for breeding habitat, while removing encroaching conifers that compete for water and light (Hankins 2013; Norgaard et al. 2016).

While fire can reduce survival and reproductive success in migratory birds on an immediate basis, particularly when they occur right before or during the nesting season (van Mantgem et al. 2015; Norgaard et al. 2016), longer-term responses to habitat changes resulting from fire vary widely depending on species and fire severity (Fontaine et al. 2009; Fontaine & Kennedy 2012). For instance, canopy nesting and foliage-foraging species tend to respond more negatively to habitat loss resulting from high-severity fire, while species that depend on shrublands and early-successional habitat (e.g., White-crowned Sparrow [*Zonotrichia leucophrys*], Yellow-breasted Chat [*Icteria virens*]) respond positively to high-severity fire (Fontaine et al. 2009; Fontaine & Kennedy 2012). Fires also creates cavities and snags used by migratory birds for feeding and nesting (Kotliar et al. 2002; Hutto 2006; Norgaard et al. 2016). Because a proportion of species respond positively to disturbances at all levels of intensity, it is likely that mixed-severity fire regimes play an important role in maintaining high levels of bird diversity on a landscape scale by supporting forests in multiple stages of succession (Fontaine et al. 2009; Fontaine & Kennedy 2012; Stephens et al. 2015).

Climate-driven changes towards greater fire severity and frequency are resulting in habitat type conversion, which affects migratory birds utilizing these areas. For instance, forests that burn very frequently may be unable to maturing enough to withstand fire before reburning, resulting in permanent conversion to montane chaparral (Airey Lauvaux et al. 2016; Tepley et al. 2017). Frequent fires also increase the likelihood of type conversion from chaparral shrublands to non-native annual grassland or degraded shrubland (Haidinger & Keeley 1993; Keeley et al. 2011; Keeley & Brennan 2012; Halsey & Keeley 2016).

Regional Wildfire Trends	
<p><i>Historical & current trends:</i></p> <ul style="list-style-type: none"> • 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) • Fire size and total area burned increased on U.S. Forest Service lands in northwestern California between 1910-2008, with the 	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> • 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) <ul style="list-style-type: none"> ○ Greatest increases in burned area (up to 400%) occur in montane forested areas in northern California (Westerling et al. 2011; Westerling 2018)

Regional Wildfire Trends	
<p>highest values occurring after 2000 (Miller et al. 2012)</p> <ul style="list-style-type: none"> • Changes in large fires (over 400 ha) in the inland northern California/Sierra Nevada region since the 1970s (Westerling 2016): <ul style="list-style-type: none"> ○ 184–274% increase in frequency ○ 270–492% increase in total area burned ○ 215% increase in length of the fire season • 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 (Miller et al. 2012; Parks et al. 2015; Law & Waring 2015; Keyser & Westerling 2017) <ul style="list-style-type: none"> ○ 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 	<ul style="list-style-type: none"> ○ Less significant increases or possible 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) <ul style="list-style-type: none"> ○ 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) <ul style="list-style-type: none"> ○ 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 Group <i>(see text for citations)</i>	
<ul style="list-style-type: none"> • <i>Immediate:</i> <ul style="list-style-type: none"> ○ Mortality and reduced reproductive success in migratory birds directly affected by fire • <i>Short-term (~2-year):</i> <ul style="list-style-type: none"> ○ Maintenance of shrublands and early-successional habitat composition and structure ○ Increased abundance of cavities and snags used for feeding and nesting • <i>Long-term:</i> <ul style="list-style-type: none"> ○ Increased bird diversity where mixed-severity fire regimes maintain landscape-scale heterogeneity 	

Insects

At endemic levels, insects act as important natural disturbances within northern California forests, contributing to a heterogeneous forest structure that supports high species diversity by creating canopy gaps, snags, and downed logs (Spies et al. 2006; Meigs et al. 2015; Fettig 2016). Warmer temperatures may contribute to earlier bark beetle emergence, the completion of additional life cycles with a single year, reduced cold-related mortality, and expanding distributions for species typically restricted to more southern ranges and/or lower elevations (Logan & Powell 2001; Powell & Logan 2005; Bentz et al. 2010). Drought-stressed trees are particularly vulnerable to insect attack (Bentz et al. 2010; Kolb et al. 2016), and outbreaks are

also more likely to occur in dense, more homogeneous forests (Bentz et al. 2010; Millar et al. 2012). Large-scale outbreaks of insects such as the mountain pine beetle (*Dendroctonus ponderosae*) can cause extensive tree mortality at a landscape scale, rapidly changing forest composition and structure (Logan & Powell 2001; Raffa et al. 2008; Hicke et al. 2016). Cavity-nesting species (most of whom are not migratory) may initially benefit from the sudden increase in dead and dying trees (Martin et al. 2006; Saab et al. 2014). As a result, large-scale insect attacks are likely to alter food and habitat availability/quality and avian community composition (Logan & Powell 2001; Martin et al. 2006; NABCI 2010).

Regional Insect Outbreak Trends	
<p><i>Historical & current trends:</i></p> <ul style="list-style-type: none"> • Bark beetle outbreaks occurred in most western U.S. forests from 1997–2012, with significant increases in beetle-related mortality after 2000 (peaking from 2008–2012; Hicke et al. 2016) • Compared to other forested areas in the western U.S., northern California experienced relatively low beetle-related mortality during the past two decades (Hicke et al. 2016) 	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> • More severe insect outbreaks are likely as temperatures increase and periods of drought become more frequent (Bentz et al. 2010; Kolb et al. 2016) • The average elevation of mountain pine beetle outbreaks is expected to shift upslope, resulting in an overall decrease in the area of forest vulnerable to outbreaks by the end of the century (Hicke et al. 2006)
Summary of Potential Impacts on Species Group <i>(see text for citations)</i>	
<ul style="list-style-type: none"> • Reduced food availability for species that depend on conifer seeds • Altered habitat suitability due to changes in forest structure • Likely changes in avian community composition 	

Disease

Migratory songbirds are sensitive to infectious diseases such as West Nile virus, which was introduced into southern California in 2003 (Reisen et al. 2004). West Nile virus can cause significant mortality in birds, and is spread through mosquito (*Culex* spp.) vectors (Marra et al. 2004; Tam et al. 2014). Patterns of vector abundance and disease transmission can be influenced by many different factors, including vector density, avian migration, weather, land use, and topography, among others (Marra et al. 2004; Owen et al. 2006; Gibbs et al. 2006; Wang et al. 2011; Tam et al. 2014). The primary climatic variables associated with the prevalence of West Nile virus are temperature and precipitation (Epstein 2001; Gibbs et al. 2006; Wang et al. 2011; Tam et al. 2014). Specifically, mild winters followed by high spring temperatures and hot, dry summers favor the transmission of West Nile virus and other mosquito-borne diseases (Epstein 2001; Johnson & Sukhdeo 2013). In the western U.S., low rainfall in the previous year has also been associated with increased incidence of West Nile virus in humans (Landesman et al. 2007). Over the coming century, warmer temperatures are expected to alter patterns of disease distribution by increasing the rate of vector survival during colder months, lengthening mosquito breeding season, and enhancing pathogen reproductive rates (Epstein 2001; Dohm et al. 2002; Marra et al. 2004; Tam et al. 2014).

Waterfowl can also be highly impacted by diseases (e.g., avian influenza, avian cholera, avian botulism), particularly where birds are highly concentrated (e.g., at wintering grounds or stopover sites; (Holmes 1996; Fleskes et al. 2010; Hénaux et al. 2012; Bianchini 2019). Climate change is likely to increase the vulnerability of waterfowl to disease as drought further reduces habitat availability, exacerbating crowded conditions (Vuln. Assessment Reviewer, pers. comm., 2019). Increased temperatures are also associated with greater risk of avian botulism (Barras & Kadlec 2000). Indirectly, climate change may also influence patterns of disease transmission as changes occur in waterfowl populations, distribution, and migration (Gilbert et al. 2008).

Regional Disease Trends	
<p><i>Historical & current trends:</i></p> <ul style="list-style-type: none"> Northwards expansion of West Nile virus in California since its detection in 2003 (Reisen et al. 2004) 	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> Range expansion in diseases currently limited by cold temperatures (Epstein 2001; Marra et al. 2004) Changes in patterns of disease prevalence and/or severity, depending on site conditions, limiting factors of the disease, and altered population movement and dynamics (Marra et al. 2004; Gilbert et al. 2008)
Summary of Potential Impacts on Species Group <i>(see text for citations)</i>	
<ul style="list-style-type: none"> Increased avian mortality 	

Dependency on habitat and/or other species

Regional experts evaluated migratory birds as having high dependency on sensitive habitats (high confidence in evaluation), low dependency on prey or forage species (high confidence), and moderate-high dependency on phenological shifts in food availability (moderate confidence).

The dependence of migratory birds on specific habitat types varies widely by functional group and species. However, all migratory birds are dependent on the availability of breeding habitat, wintering grounds, and migratory stopover sites (Dolman & Sutherland 1995; Stralberg et al. 2010; Small-Lorenz et al. 2013; Galbraith et al. 2014). Habitat loss or degradation due to climate change, disturbances, or anthropogenic stressors in any of these can reduce avian survival and/or reproductive success, leading to population declines (Page & Gill 1994; Stralberg et al. 2010; Small-Lorenz et al. 2013; NABCI 2014, 2016; Galbraith et al. 2014; Seavy et al. 2018). Shorebirds, in particular, are vulnerable to extreme changes in coastal habitat availability due to sea level rise (Galbraith et al. 2002, 2014). Shorebirds and waterfowl that breed in the Arctic are also likely to experience rapid rates of change in their breeding grounds because of disproportionately high temperature increases and climate-driven disturbances in that region (Melfotte et al. 2007; Gilbert et al. 2008).

Climate change is also likely to alter the timing of seasonal patterns related to migration and breeding (Gordo 2007; Ackerman et al. 2011; Mayor et al. 2017; Halupka & Halupka 2017;

Seavy et al. 2018; Furnas & McGrann 2018). Warmer temperatures have already been correlated with earlier spring arrival in migratory species (Mayor et al. 2017; Furnas & McGrann 2018), as well as changes in the onset of breeding behavior and the length of the breeding season (Halupka & Halupka 2017; Furnas & McGrann 2018). Because migration and breeding are generally timed to coincide with peak food availability, phenological shifts in plant and insect production could impact migratory bird survival and reproductive success (Both et al. 2006; Leech & Crick 2007; NABCI 2010; Mayor et al. 2017).

Sensitivity and current exposure to non-climate stressors

Regional experts evaluated shorebirds and waterfowl as having moderate-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). Songbirds were evaluated as having moderate-high sensitivity to non-climate stressors (high confidence), with an overall moderate current exposure (high confidence). Key non-climate stressors that affect migratory birds include land-use conversion (for residential/commercial development, agriculture, and energy), fire exclusion and suppression, recreation, pollution, livestock grazing, and hunting.⁶

Land-use conversion for residential/commercial development, agriculture, and energy

Land-use conversion has resulted in habitat loss and fragmentation for many migratory birds, and has been a major contributor to population declines for many species (NABCI 2014, 2016). For instance, energy development (e.g., wind farms, powerlines) and the expansion of residential/commercial development has had significant impacts on obligate grassland chaparral species (NABCI 2010, 2014). Land-use conversion to agricultural uses have also resulted in the loss of many wetland and riparian habitats in northwestern California, particularly in and around the Sacramento Valley (Gilmer et al. 1982; RHJV 2004).

Fire exclusion and suppression

Fire suppression has reduced the occurrence and extent of fire across large portions of the landscape in northern California (Safford & Van de Water 2014; Steel et al. 2015; Norgaard et al. 2016), which has resulted in overall denser forest conditions, shifts in species composition, and the loss of complex early-successional habitats (Skinner et al. 2006; Skinner & Taylor 2006; Stuart & Stephens 2006; McIntyre et al. 2015; Safford & Stevens 2017). A buildup of fuels can also alter patterns of fire severity, potentially influencing bird abundance and community composition directly (i.e., through mortality) or indirectly (i.e., through changes in habitat structure; Alexander et al. 2004). Because mixed-severity fires are associated with high avian diversity on the landscape scale (Fontaine et al. 2009; Fontaine & Kennedy 2012; Stephens et al. 2015), fire exclusion over the past century has likely influenced migratory songbird diversity and community composition in forested landscapes (Alexander et al. 2004; Furnas & McGrann 2018). Oak woodlands have also declined significantly across the region as a result of fire

⁶ Non-climate stressors presented are those ranked as having a moderate or higher impact on this species group; additional non-climate stressors that may influence the species group to a lesser degree include invasive species, dams and water diversions, and timber harvest.

suppression (Jimerson & Carothers 2002), which impacts species closely associated with oaks such as the Bullock's Oriole (*Icterus bullockii*) and Oak Titmouse (*Baeolophus inornatus*; Altman & Stephens 2012).

Shrub-associated species (e.g., Yellow-breasted Chat) are also sensitive to fire suppression and fuel treatment activities (e.g., mastication), which are often utilized to reduce fuel loads in shrublands identified as potential fire hazards (Perchemlides et al. 2008; Wilkin et al. 2017). These treatments significantly affect the structure and composition of chaparral and oak-dominated ecosystems (Perchemlides et al. 2008; Wilkin et al. 2017), reducing habitat suitability for shrub-associated songbirds (Seavy et al. 2008).

Recreation

Recreational use of beaches has a significant impact on breeding and wintering shorebirds, primarily by increasing rates of egg and chick predation by corvids (*Corvus* spp.; e.g., ravens, crows) (Colwell et al. 2005; Burrell & Colwell 2012; Hardy & Colwell 2012; Dinsmore et al. 2017). Nest predation reduces reproductive success and has been implicated in the decline of Western Snowy Plover populations (Colwell et al. 2005; Burrell & Colwell 2012; Hardy & Colwell 2012; Dinsmore et al. 2017). Corvids are associated with areas of high human activity, such as heavily used recreational beaches and campgrounds, where they are attracted to garbage and other food sources (Hardy & Colwell 2012).

Recreational activities and associated human presence on beaches and dunes also degrades habitat quality for shorebirds (Pfister et al. 1992). Humans, dogs, and recreational vehicles can destroy nests, disturb roosting shorebirds, and/or keep adults from brooding chicks on heavily used beaches (Colwell et al. 2005; Page et al. 2009; Hardy & Colwell 2012), potentially attracting predators to flushed birds (Hardy & Colwell 2012) and/or reducing overall fitness by increasing metabolic activity or altering foraging behavior and food intake (Schlacher et al. 2013).

Pollution

Shorebirds and waterfowl can be significantly affected by offshore oil spills, which often result in acute mortality for large numbers of birds (Henkel et al. 2012; Perez et al. 2017). Because even a small amount of oil can reduce the ability of feathers to insulate a bird, oiled birds are vulnerable to hypothermia (Leighton 1993). Ingestion of oil, such as occurs during preening, (Leighton 1993; Briggs et al. 1996) can also cause gastrointestinal and respiratory problems, kidney or liver failure, and many other negative and potentially lethal effects (Briggs et al. 1996). Shorebirds are particularly vulnerable because they probe-forage within the intertidal zone, increasing the potential for them to ingest oil and/or experience significant declines in the availability of invertebrate prey also impacted by oil (Henkel et al. 2012). Lightly oiled birds may also experience flight impairment which could delay their arrival to breeding, wintering, and/or stopover sites (Perez et al. 2017). Together with behavioral changes and other non-lethal effects of oiling, migratory birds may not survive travel over long distances and/or may experience reduced reproductive success (Henkel et al. 2012).

Contaminants such as pesticides and mercury are also important sources of pollution. Mercury-polluted streams from abandoned mercury mines caused significant reproductive declines in Osprey (*Pandion haliaetus*) and Western and Clark's Grebes (*Aechmophorus occidentalis*, *Aechmophorus clarkii*) around Clear Lake, likely due to high mercury concentrations in prey fish (Anderson et al. 2008). Pesticide drift from agricultural areas affects migratory birds directly by causing lethal or sublethal effects following the ingestion of contaminated insects or neonicotinoid-coated seeds and indirectly by reducing insect prey (Hladik et al. 2018). High concentrations of neonicotinoid pesticides have been implicated in farmland bird population declines (Hallmann et al. 2014).

Livestock grazing

Grazed areas are associated with reduced avian abundance and altered community composition across the western U.S., with some of the most significant impacts noted among long-distance migratory, shrub-nesting, and/or foliage-gleaning species (Tewksbury et al. 2002; Alexander et al. 2008). Livestock grazing is frequently associated with riparian areas, grasslands, and oak woodlands particularly on private lands (Campbell & Allen-Diaz 1997; Tewksbury et al. 2002; RHJV 2004; Alexander et al. 2008; NABCI 2010). Livestock can directly disturb breeding birds by knocking over nests in willow thickets and other shrubby areas and/or trampling the eggs of ground-nesting birds such as the Lincoln's Sparrow (*Melospiza lincolnii*; Sanders & Flett 1989; RHJV 2004). Grazing also reduces grasses and herbaceous vegetation, resulting in changes in riparian habitat composition and structure and associated declines in the quality and availability of nesting and foraging habitat (Sanders & Flett 1989; Campbell & Allen-Diaz 1997; RHJV 2004). However, impacts on migratory birds vary depending on grazing intensity (Alexander et al. 2008), and grazing at low or moderate intensities can benefit some species, such as by providing a mosaic of vegetation heights in coastal pastures (Colwell & Dodd 1995) or preventing the succession of grasslands to woody vegetation (NABCI 2010).

Hunting

Hunting can significantly reduce populations of wintering waterfowl, and is the primary cause of mortality in some species such as the northern pintail (Fleskes et al. 2007). Hunting can also impact avian behavior, such as daily movement patterns and habitat selection (Casazza et al. 2012).

Adaptive Capacity

Migratory birds were evaluated by regional experts as having high overall adaptive capacity (high confidence in evaluation).

Species group extent, integrity, connectivity, and dispersal ability

Regional experts evaluated migratory birds as having a high geographic extent (high confidence in evaluation) and a high degree of connectivity between populations (high confidence). Overall health and functional integrity were evaluated as moderate-high for songbirds (high confidence) and moderate for shorebirds and waterfowl (high confidence).

Regional experts evaluated migratory birds as having a high dispersal ability (high confidence in evaluation). Barriers to dispersal were evaluated as having a low-moderate impact on the species group (high confidence). Loss or alteration of migratory stopover sites was identified as the primary barrier to dispersal.⁷

Migratory birds in northern California utilize a wide range of habitat types across the region, including beaches, estuaries, wetlands, grasslands, shrublands, and forests (Stralberg et al. 2010; Altman & Stephens 2012; Gardali et al. 2012; McGrann & Furnas 2016). Changing climate conditions may shift the location and/or alter the size of breeding and wintering ranges for migratory birds, contributing to changes in avian community composition and population size and health (Stralberg et al. 2009; Tingley et al. 2012; Langham et al. 2015). Habitat loss and fragmentation in breeding and/or wintering areas have contributed to population declines in many migratory bird species (CDFW 2015; NABCI 2016), and changing climate conditions may drive further declines, especially among long-distance migrants (Both et al. 2009; NABCI 2010). Generalist species (i.e., those that can live in multiple habitats) are typically of lower conservation concern due to their greater flexibility (NABCI 2016).

Migratory birds are highly mobile and can travel long distances to reach suitable habitat and food resources (Dolman & Sutherland 1995; NABCI 2016). However, increased habitat connectivity decreases foraging energy requirements (Elphick 2000; Ackerman et al. 2006) and enhances breeding success (Stephens et al. 2003), dispersal, and gene flow (Dolman & Sutherland 1995; Bélisle & St. Clair 2001; Stephens et al. 2003). Thus, connectivity across landscapes is a key functional element in adapting to climate change (Keeley et al. 2018). The loss or alteration of key migratory stopover sites can result in greater vulnerability to population declines, particularly for species that already have small population sizes and restricted distributions (NABCI 2016). Long-distance migratory shorebirds, in particular, have experienced significant population declines due to a combination of the loss of key migratory stopover sites and climate change impacts on northern breeding grounds (NABCI 2016). Those species of which a large proportion of the population passes through a bottleneck point along their migration route (Iwamura et al. 2013). For instance, roughly 40% of the Pacific Brant population feed in Humboldt Bay eelgrass (*Zostera maritima*) beds during their migration from Mexico to the coast of British Columbia and Alaska (Moore et al. 2004; USFWS 2018), and may be vulnerable to habitat loss due to sea level rise (Shaughnessy et al. 2012). Songbirds migrating to and from northern California may be particularly impacted by the loss of desert stopover sites (Vuln. Assessment Workshop, pers. comm., 2017).

Intraspecific/life history diversity

Regional experts evaluated migratory birds as having high life history diversity (high confidence in evaluation), high genetic diversity (high confidence), high behavioral plasticity (high confidence), and high phenotypic plasticity (high confidence).

⁷ 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 land-use conversion.

Migratory birds in northern California are a highly diverse group, representing a wide array of migration strategies, life history traits, foraging guilds, and habitat preferences (Motroni 1984; Dolman & Sutherland 1995; Stralberg et al. 2010; Gardali et al. 2012; Galbraith et al. 2014; DiGaudio et al. 2015; Mayor et al. 2017; Furnas & McGrann 2018). In general, species with higher levels of genetic variation, phenotypic diversity, and/or behavioral plasticity are more likely to shift migration timing and/or route in response to changing climate conditions and habitat loss (Dolman & Sutherland 1995; Ackerman et al. 2011; Gilroy et al. 2016; Mayor et al. 2017; Bay et al. 2018). A study of northern California songbirds found that Neotropical migrants appear to have less variation in the timing of peak vocal activity in the spring (a proxy for breeding; Furnas & McGrann 2018), which is consistent with other studies suggesting the potential for greater phenological mismatches in long-distance migrants (Pulido & Widmer 2005; Gilroy et al. 2016; Mayor et al. 2017). However, some migrants do show evidence of flexibility in response to environmental conditions; for instance, Black-headed Grosbeaks (*Pheucticus melanocephalus*) arrive on their breeding grounds earlier during El Niño years (Ackerman et al. 2011), and flexibility in breeding behavior has been noted in Arctic shorebirds in response to annual weather variations (Meltofte et al. 2007). Still other species, such as the snowy plover, have demonstrated behavioral plasticity in nest site selection that may increase reproductive success (Herman & Colwell 2015). It is important to note, however, that the accelerated rate of change projected over the coming century is likely to make it much more difficult for migratory birds to adjust to changing habitat conditions through behavioral or evolutionary adaptations (Diffenbaugh & Field 2013).

Resistance and recovery

Regional experts evaluated waterfowl and songbirds as having moderate-high resistance to climate stressors and natural disturbance regimes (high confidence in evaluation), while shorebirds were evaluated as having low-moderate resistance (high confidence). All groups were evaluated as having high recovery potential (high confidence).

The high mobility of migratory birds confers resistance to changing conditions by allowing individuals to avoid disturbances, seek out higher-quality habitat, shift their range, and/or change their migration strategy (Dolman & Sutherland 1995; Ackerman et al. 2011; van Mantgem et al. 2015; Mayor et al. 2017; Porzig et al. 2018). However, the dependence of this species group on habitat availability in disparate locations increases the risk that one or more sites will be affected by climate and/or non-climate stressors (Dolman & Sutherland 1995; Small-Lorenz et al. 2013) and/or that shifts in the timing of migration and breeding will be unable to keep up with rapid shifts in plant and insect phenology (Both et al. 2006; Leech & Crick 2007; Mayor et al. 2017).

By contrast, population recovery is dependent on adult survival and reproductive rates (Vuln. Assessment Workshop, pers. comm., 2017). Thus, species that can re-nest following the loss of eggs and chicks and/or those that produce multiple broods in a single year may be less vulnerable to disturbance and extreme climatic conditions (Halupka & Halupka 2017). In long-

lived species such as shorebirds, adult survival may have a more significant impact on long-term population growth than nest success (Eberhart-Phillips & Colwell 2014; Herman & Colwell 2015). Increased climate stressors, more frequent and/or severe disturbances, and continued habitat degradation and loss may prevent population recovery, particularly for species that are already in decline (NABCI 2010).

Management potential

Public and societal value

Regional experts evaluated migratory birds as having high public and societal value (high confidence in evaluation).

Migratory birds have significant public appeal, and are valued by birders, hunters, and many others (Vuln. Assessment Workshop, pers. comm., 2017). This species group receives a relatively high amount proportion of federal and state conservation funding, as well as recreational spending (Vuln. Assessment Workshop, pers. comm., 2017). For instance, funds for wetland protection and restoration are derived, in part, from the sale of Federal Migratory Bird Hunting and Conservation Stamps (“duck stamps”), and hunters support many policies and management practices that benefit waterfowl (Gilmer et al. 1982; NAWMP 2012). However, the number of hunters in the U.S. has declined since the 1970s, with possible implications for the generation of revenue that supports waterfowl conservation and management (NAWMP 2012). Sudden population declines of charismatic species do have the potential to galvanize public and societal support for conservation, such as occurred prior to the ban of many pesticides in the 1970s, and may drive increased support of management for climate impacts (Vuln. Assessment Workshop, pers. comm., 2017).

Northern California is recognized as a significant region within the Pacific Flyway, in large part due to the importance of Humboldt Bay as a critical stopover site for migrating shorebirds and waterfowl (Page et al. 1999; Hickey et al. 2003; Colwell & Feucht 2018). The Humboldt Bay National Wildlife Refuge was established in 1971 to protect wintering and stopover habitat for migratory birds (USFWS 2018), and in 1998 Humboldt Bay was designated as a Site of International Importance by the Western Hemisphere Shorebird Reserve Network (Colwell & Feucht 2018; USFWS 2018), though it is not recognized under the Ramsar Convention (Vuln. Assessment Reviewer, pers. comm., 2019). Over the past several decades, over 260 species have been documented in the area, including 34 shorebird species and 31 waterfowl species (USFWS 2018). Humboldt Bay can host peak numbers of over 100,000 shorebirds and 50,000 geese in January and February (Vuln. Assessment Reviewer, pers. comm., 2019), including large proportion of the populations of Pacific Brant (Moore et al. 2004), Aleutian Cackling Geese (Black et al. 2004), and Marbled Godwit (*Limosa fedoa*; Vuln. Assessment Reviewer, pers. comm., 2019). During the spring migration, a recent study has documented use by over half a million shorebirds, suggesting that this region may be even more important than previously recognized (Colwell & Feucht 2018).

While birds face many threats that are exacerbated by climate change, the history of successful bird conservation in the U.S. can serve as a model to guide broader efforts to conserve functional ecosystems (NABCI 2016; Vuln. Assessment Reviewer, pers. comm., 2019). For instance, collaborative conservation efforts such as the North American Waterfowl Management Plan have allowed population recovery for many species by coordinating scientific research and management across species' ranges, while also taking advantage of policy (e.g., North American Wetlands Conservation Act) and associated funding streams (NABCI 2016). These efforts have been supported by the formation of regional cooperative partnerships called Migratory Bird Joint Ventures that address habitat conservation within their geographic area (NABCI 2010, 2016).

Management capacity and ability to alleviate impacts⁸

Regional experts evaluated the potential for reducing climate impacts on migratory birds through management as high (high confidence in evaluation).

The scientific literature has identified a number of management strategies that are likely to increase the resilience of migratory birds to changes in climate stressors and disturbance regimes by increasing habitat availability and connectivity (DiGaudio et al. 2015; Dybala et al. 2018; Reiter et al. 2018), reducing nest predation and brood parasitism (RHJV 2004; Eberhart-Phillips & Colwell 2014; Dinsmore et al. 2017), restoring natural disturbance regimes such as fire and flooding to increase resilience to the effects of climate change (CalPIF 2002a, 2002b; Berlanga et al. 2010; NABCI 2010; Alexander et al. 2017), and protecting potential climate refugia (Seavy et al. 2009; Alexander et al. 2017). However, the potential for management to reduce climate impacts on migratory birds varies considerably across species and functional groups (Vuln. Assessment Workshop, pers. comm., 2017). For instance, the potential to manage habitat availability for waterfowl is high as long as water is available (Matchett & Fleskes 2017; Vuln. Assessment Workshop, pers. comm., 2017). In order to be effective, conservation activities focused on migratory birds must take into account multiple factors, including habitat structure, nest site availability, food resources, microclimate conditions, predation risk, land use in adjacent habitats, and connectivity (Stephens et al. 2003; RHJV 2004; Seavy et al. 2009; Ackerman et al. 2011; Dybala et al. 2017).

Habitat conservation across the full life cycle of migratory birds is critical, but management of transcontinental species can present additional challenges related to coordinating conservation across geopolitical boundaries (Small-Lorenz et al. 2013; Vuln. Assessment Workshop, pers. comm., 2017). However, improved data collection and management and habitat mapping are being utilized by expanding networks of conservation-focused agencies and organizations, which has resulted in successful coordination of research, planning, and management at large scales (NABCI 2010, 2016; Stephens et al. 2011). Additionally, migrant landbirds appear to respond readily to conservation actions on their breeding grounds even when researchers may not know where migrants are most limited in their lifecycle (Vuln. Assessment Reviewer, pers.

⁸ Further information on climate adaptation strategies and actions for northern California can be found on the project page (<https://bit.ly/31AUGs5>).

comm., 2019). For example, the removal of cattle from a 40,000-acre Cascade-Siskiyou National Monument in nearby southern Oregon resulted in increases in abundance and/or reduced rates of decline for migratory birds in areas where heavy grazing was eliminated (Gillespie et al. 2018).

PIF has developed and tested a strategy for using land management- and policy-relevant science as a catalyst for improving ecosystem management (Alexander 2011; Rosenberg et al. 2016). This approach is based on using multiple bird species as indicators of current and desired ecological conditions, and should be used to ensure the effectiveness of climate-smart ecosystem conservation efforts (Alexander 2011; Rosenberg et al. 2016). It involves using PIF population and habitat objectives along with data from bird monitoring to assess management needs, set measurable targets, design management to meet these targets, and measure the effectiveness of actions (Alexander 2011; Rosenberg et al. 2016).

In coastal habitat utilized by shorebirds and waterfowl, soft adaptation approaches may allow the inland migration of eelgrass, dunes, and coastal wetlands as sea levels rise (Galbraith et al. 2002; Vuln. Assessment Workshop, pers. comm., 2018). For breeding shorebirds nesting on beaches and dunes, management strategies will also require a focus on predator reduction, as well as limiting human disturbances around nest sites (Eberhart-Phillips & Colwell 2014). For Western Snowy Plovers, reducing rates of nest predation has had a significant positive impact on nest survival (Eberhart-Phillips & Colwell 2014; Dinsmore et al. 2017), and has the potential to increase population growth rates (Eberhart-Phillips & Colwell 2014). While nest exclosures have been demonstrated as effective ways to increase hatching success, they do not appear to have a significant benefit on overall reproductive success (Herman & Colwell 2015; Dinsmore et al. 2017). Thus, recent efforts have placed more emphasis on directly reducing predator populations in breeding areas through harassment, culling, and translocation of predators (Dinsmore et al. 2017). Limiting human disturbance on sandy beaches (e.g., by fencing or excluding recreational vehicle use) also has the potential to increase shorebird reproductive success and/or adult survival (Wilson & Colwell 2010; Eberhart-Phillips & Colwell 2014; Maslo et al. 2018).

Management actions designed to maintain the availability of freshwater wetlands and flooded croplands are considered one of the most effective ways to ameliorate the impacts of drier conditions on habitat availability for shorebirds and waterfowl, especially in agricultural areas where water demand is high (Ackerman et al. 2011; DiGaudio et al. 2015; Strum et al. 2017; Reiter et al. 2018). Specifically, multiple studies have assessed the effectiveness of incentive programs that pay farmers and landowners to provide flooded areas for waterfowl and shorebirds, either by utilizing beneficial agricultural practices (e.g., flooding post-harvest rice fields) or removing environmentally-sensitive wetlands from active agricultural use (DiGaudio et al. 2015; Golet et al. 2018; Reiter et al. 2018). These programs are particularly beneficial during periods of severe drought, when reduced water availability in the region can discourage the management of agricultural areas and wetlands that provide vital staging areas for migrating and wintering waterfowl (Kahara et al. 2012; Matchett & Fleskes 2017).

For migratory songbirds, protecting and restoring riparian areas has been demonstrated as an effective way to increase habitat availability, enhance connectivity, and create climate refugia (Gardali et al. 2006; Seavy et al. 2009; DiGaudio et al. 2015; Dybala et al. 2018; Rockwell & Stephens 2018). Riparian areas support high diversity of both breeding and wintering songbirds (Dybala et al. 2015; DiGaudio et al. 2015), and are naturally resilient to climate changes and disturbances (e.g., flooding; Seavy et al. 2009). Riparian restoration often focuses on restoring natural hydrological processes, and increasing native plant cover and structural diversity through planting and/or invasive species removal (Gardali et al. 2006; DiGaudio et al. 2015; Dybala et al. 2018; Rockwell & Stephens 2018). Other strategies that may ameliorate the impacts of habitat loss and other anthropogenic stressors for migratory songbirds include the restoration of natural fire regimes in shrublands and oak woodlands (CalPIF 2002a; Altman & Stephens 2012), and management of grazing intensity and timing (Sanders & Flett 1989; Gillespie et al. 2018), among others. Tools such as the Conservation Ranking Map within the Pacific Northwest Climate Change Avian Vulnerability tool (available from <https://www.avianknowledgenorthwest.net/dsts/interactive-maps/1-pnw-models>) can assist managers in identifying areas where conservation work for riparian, conifer, grassland, and oak woodland species should be prioritized, based on current and projected species abundance under several climate change scenarios (Veloz et al. 2013, 2015; Alexander et al. 2017).

Ecosystem services

Migratory birds provide a variety of ecosystem services, including:

- Provisioning of food and ornamental resources (Vuln. Assessment Workshop, pers. comm., 2017);
- Regulation of insect pests and disease (Kross et al. 2016; Gaston et al. 2018);
- Support of pollination (i.e., by hummingbirds, warblers; Vuln. Assessment Workshop, pers. comm., 2017), seed dispersal, and nutrient cycling (Gaston et al. 2018); and
- Cultural/tribal uses for spiritual/religious purposes, knowledge systems, educational values, aesthetic values, social relations, sense of place, cultural heritage, inspiration, and recreation (Vuln. Assessment Workshop, pers. comm., 2017; Gaston et al. 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),⁹ 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.¹⁰

⁹ Sensitivity and adaptive capacity elements were informed by Lawler 2010, Glick et al. 2011, and Manomet Center for Conservation Sciences 2012.

¹⁰ 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:

$$\text{Vulnerability} = [(\text{Climate Exposure} * 0.5) \times \text{Sensitivity}] - \text{Adaptive Capacity}$$

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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