



Salamanders

Northern California Climate Change Vulnerability Assessment Synthesis

An Important Note About this Document: *This document represents an initial evaluation of vulnerability for salamanders 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 species vulnerability to changing climate conditions, and to provide a foundation for developing appropriate adaptation responses.*

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Table of Contents

Species Group Description	1
Executive Summary	2
Sensitivity and Exposure	3
<i>Sensitivity and future exposure to climate and climate-driven factors</i>	5
<i>Sensitivity and future exposure to changes in natural disturbance regimes</i>	11
<i>Dependency on habitat and/or other species</i>	16
<i>Sensitivity and current exposure to non-climate stressors</i>	16
Adaptive Capacity	19
<i>Species group extent, integrity, connectivity, and dispersal ability</i>	19
<i>Intraspecific/life history diversity</i>	21
<i>Resistance and recovery</i>	22
<i>Management potential</i>	22
Public and societal value	22
Management capacity and ability to alleviate impacts	23
Ecosystem services.....	24
Recommended Citation	25
Literature Cited	25
Vulnerability Assessment Methods and Application	36

Species Group Description

The complex geology and changing environmental conditions in California have led to a diverse assemblage of locally endemic and regionally distributed salamander species, some of which are extreme habitat specialists (Petranka 1998; Bury & Pearl 1999; Thomson et al. 2016). These amphibians occur in a variety of terrestrial and aquatic habitats, and can be locally abundant (Welsh & Lind 1991; Good & Wake 1992; Petranka 1998) or inhabit very restricted ranges (Nauman & Olson 2004; Thomson et al. 2016; Bingham et al. 2018).

This assessment provides an overview of the semi-aquatic and terrestrial salamanders of northern California, focusing on both representative species and those that are particularly vulnerable to climate and non-climate stressors. These include the coastal giant salamander (*Dicamptodon tenebrosus*; a member of the Pacific giant salamander species complex), southern torrent salamander (*Rhyacotriton variegatus*), northwestern salamander (*Ambystoma gracile*), and plethodontid (lungless) salamanders (e.g., California slender salamander [*Batrachoseps attenuatus*], the Shasta salamander complex [*Hydromantes shastae*, *H. samweli*, and *H. wintu*], the *Ensatina eschscholtzii* complex, *Aneides* spp., and *Plethodon* spp.), among other species (Nauman & Olson 2004; Norgaard et al. 2016; Thomson et al. 2016; Bingham et al. 2018; Vuln. Assessment Reviewer, pers. comm., 2019).

Executive Summary

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

Salamanders	Rank	Confidence
Sensitivity	Moderate-High	Moderate
Future Exposure	Moderate-High	Moderate
Adaptive Capacity	Low-Moderate	Low
Vulnerability	Moderate-High	Moderate

Sensitivity & Exposure Summary	<p><u>Climate and climate-driven factors:</u></p> <ul style="list-style-type: none"> Precipitation (amount/timing), soil moisture, snowpack amount, timing of snowmelt and runoff, streamflow, water temperature, drought, air temperature, heat waves <p><u>Disturbance regimes:</u></p> <ul style="list-style-type: none"> Wildfire, disease, flooding <p><u>Non-climate stressors:</u></p> <ul style="list-style-type: none"> Dams and water diversions, residential and commercial development, pollution and poisons, fire exclusion/suppression, timber harvest, invasive species
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Salamanders are vulnerable directly (e.g., impaired respiration, mortality) and indirectly (i.e., through habitat change) to climate stressors, disturbance regimes, and non-climate stressors. Because some salamander species rely on distinct breeding, foraging, and dispersal habitat types for different life stages, they are likely vulnerable to an assortment of stressors over the course of their lives. Salamanders are sensitive to factors that result in warmer, drier terrestrial habitat and altered stream and pond hydroperiods. Impacts on terrestrial habitats, such as changes in soil moisture and vegetation, can directly affect juvenile and adult salamanders as well as developing embryos. Semi-aquatic salamanders are highly sensitive to factors that result in degradation or loss of streams, vernal pools, and permanent ponds. Fire, post-fire flooding, and debris flows also degrade or destroy aquatic and terrestrial habitat. Salamanders are subject to ongoing habitat loss and fragmentation from dams and water diversions, residential and commercial development, pollution, timber harvest, and invasive species, which restrict

movement and habitat recolonization. Cumulatively, habitat drying, fragmentation, and loss are likely to reduce salamander abundance and recruitment and may result in more isolated populations and restricted ranges due to highly specific habitat requirements in a landscape undergoing significant ecological transformations.

Adaptive Capacity Summary	<p><u>Factors that enhance adaptive capacity:</u></p> <ul style="list-style-type: none"> + Potential for behavioral response to unfavorable conditions, which could buffer effects of limited physiological adaptive capacity + High local abundance + Capability to persist in small remnant populations <p><u>Factors that undermine adaptive capacity:</u></p> <ul style="list-style-type: none"> – High habitat specificity including associations with narrow thermal and moisture regimes – Reduced genetic diversity and risk of extirpation due to habitat fragmentation – Limited physiological adaptive capacity (may not keep up with rapid environmental change) – Low public awareness of this species group
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Salamander distributions in northwestern California vary, with some species being widely but patchily distributed and others found only in very restricted locations. Both limited-range and widespread species in isolated habitats are highly vulnerable to habitat fragmentation/loss and changes that increase the risk of desiccation. Small, isolated populations of salamanders generally have less genetic diversity than more widely distributed species, especially in higher elevation habitats where dispersal is more difficult. Salamanders are able to exploit nearby microhabitats that offer thermal and/or hydrological refugia from climate change, but this behavioral plasticity is unlikely to compensate for all climate impacts. Life history traits also play a role in the ability of salamander species to accommodate and/or adapt to change. For instance, longer-lived species may be resilient to occasional extreme climate years; similarly, species with greater fecundity are more likely to survive ‘bust years’ due to adverse conditions. Over the longer term, some species may adjust to warmer temperatures or shorter active seasons by decreasing body size, but this response is unlikely to stop population losses from climate changes affecting multiple parts of a species life history. Although funding and other resources for salamander conservation are much less than for at-risk birds and mammals, there is some societal and regulatory support for protection of salamanders and their habitats. Potential management and conservation actions include enhancing habitat complexity to create microrefugia and minimizing land-use practices that degrade habitat and prevent dispersal.

Sensitivity and Exposure

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

Current statewide salamander distribution data are incomplete and projections of future distribution are not available. However, it is likely that the range of many species will contract as cool, moist forest microclimates are lost (McMenamin et al. 2008; Thomson et al. 2016) and headwater streams become warmer (Bury 2015). Studies of *plethodontid* salamanders in other regions of the country suggest that loss of climatically-suitable habitat may impact species with more southern ranges and/or smaller ranges to a greater degree (Milanovich et al. 2010).

Potential Changes in Species Group Distribution
<ul style="list-style-type: none"> • Likely range contractions due to warmer, drier climate conditions • Potential refugia include springs and late seral forests
Source(s): Milanovich et al. 2010; Bury 2015; Thomson et al. 2016; Frey et al. 2016; Vuln. Assessment Reviewer, pers. comm., 2019

More recent studies modeling climate sensitivity in Oregon amphibians found that several *plethodontids* and one headwater stream-associated species were modeled as having very narrow climatic niche breadths (i.e., range of historical climate conditions within a species' area of occurrence), suggesting high climate sensitivity. These included the Siskiyou Mountains salamander (*Plethodon stormi*), California slender salamander, southern torrent salamander, Del Norte salamander (*P. elongatus*), black salamander (*Aneides flavipunctatus*), clouded salamander (*A. ferreus*), and Dunn's salamander (*P. dunni*). By contrast, the northwestern salamander and long-toed salamander (*Ambystoma macrodactylum*) occurred at sites with a broader range of composite climate conditions, suggesting lower climate sensitivity. After incorporating the geographic rarity of these species (from an Oregon perspective), Mims et al. (2018) found that the Siskiyou Mountains salamander had the highest values (i.e., greatest concern) among all amphibians modeled. Southern torrent salamanders, Del Norte salamanders, California slender salamanders, and black salamanders also scored high on the integrated rarity and climate sensitivity index, which may help inform assessments in California.

Climate sensitivity assessments were also conducted for selected Pacific Northwest salamander species by Case (2014), using a combination of literature review and expert opinion to rank species' climate sensitivity. Of the species that occur within the northern California study area, the most sensitive species were the southern torrent salamander (score of 84 out of 100), Siskiyou Mountains salamander (score of 79) and black salamander (score of 77).¹

The existence of habitat refugia will be important for survival in a changing climate (Humphries & Baldwin 2003). Thermal refugia could occur in late seral forests with high canopy cover (Frey et al. 2016). Talus slopes also offer an environment that is buffered from thermal extremes, though they are very patchily distributed (Vuln. Assessment Reviewer, pers. comm., 2019). Spring water sources are more likely to continue providing suitable habitat for aquatic species in a warmer climate (Vuln. Assessment Reviewer, pers. comm., 2019).

¹ In addition, 12 amphibian species are included in the Pacific Northwest Climate Change Vulnerability Assessment developed by M. Case and others (<http://www.climatevulnerability.org/>).

Sensitivity and future exposure to climate and climate-driven factors

Regional experts evaluated salamanders 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 salamanders include precipitation (amount/timing), soil moisture, snowpack amount, timing of snowmelt and runoff, streamflow, water temperature, drought, air temperature, and heat waves.²

Precipitation (amount/timing) and soil moisture

Many northern California salamander species rely on precipitation to maintain rain-dominated aquatic systems and provide moist forest microsites (Vuln. Assessment Reviewer, pers. comm., 2019). Thus, precipitation declines would likely lead to the loss of suitable breeding and foraging habitat within both aquatic and terrestrial systems (Blaustein et al. 2010; Thomson et al. 2016). For instance, terrestrial *plethodontid* salamanders must maintain moist skin that facilitates gas exchange, so they are typically most active (i.e., foraging, defending territories, seeking mates) at night when the relative humidity is high (Petranka 1998). During periods of decreased precipitation and soil moisture, individuals move underground or beneath moist decaying logs to avoid becoming desiccated (Spotila 1972; Blaustein et al. 2010).

Changes in precipitation and soil moisture that affect vegetation (i.e., canopy cover) can directly impact adult and juvenile salamanders and the developing embryos of fully terrestrial species through morbidity and mortality (Blaustein et al. 2010). A recent landscape-scale gene flow analysis found that, in Oregon, forest cover was the top predictor of gene flow in the southern torrent salamander and another *Rhyacotriton* species (Emel et al. 2019). These results underscore the importance of forest cover in maintaining cool, moist surface microclimates for these moisture-reliant species, and emphasizes the need to consider microclimates within breeding, foraging, and dispersal habitats for amphibians with complex life histories (Emel et al. 2019). Other factors that may affect moisture conditions in salamander habitats include aquatic proximity and riparian reserves (Brososke et al. 1997; Anderson et al. 2007; Rykken et al. 2007; Olson & Kluber 2014), downed wood (Kluber et al. 2009), and rocky substrates, north-facing aspects and hill-shading (e.g., for the Siskiyou Mountains salamander; Olson et al. 2009; Reilly et al. 2009).

Periods of increased precipitation would increase humidity on the forest floor, likely benefitting terrestrial salamanders that are unable to forage in dry leaf litter (Jaeger 1979; Jaeger et al. 1995; Walton 2005). Increased precipitation levels have also been shown to affect reproductive success in many species of salamanders (Scott & Fore 1995; Harris & Ludwig 2004). For instance, above-average rainfall and associated improvements in terrestrial prey bases may contribute to increases in clutch size (Milanovich et al. 2006) and improved offspring health (Blaustein et al. 2010).

² All climate and climate-driven factors presented were ranked as having a moderate or higher impact on this species group.

Regional Precipitation & Soil Moisture Trends ³	
<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) • No trends available for soil moisture 	<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)⁴ • 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) • Decreased top-level soil moisture is likely even if precipitation increases due to temperature-related changes in evaporative demand (Pierce et al. 2018)
Summary of Potential Impacts on Species Group <i>(see text for citations)</i>	
<ul style="list-style-type: none"> • Loss of suitable breeding and foraging habitat where precipitation declines • Increased mortality of adult and juvenile salamanders as well as developing embryos due to declines in soil moisture and the loss of moist microsites 	

Snowpack amount and timing of snowmelt and runoff

Declines in snowpack amount and earlier timing of snowmelt and runoff are likely to alter stream hydrology and terrestrial habitat moisture availability, especially after the spring runoff period (McMenamin et al. 2008; Thomson et al. 2016). Hydrologic alterations due to these changes may drive loss or degradation of sensitive habitats (e.g., ephemeral ponds), which could result in salamander population declines or local extirpations (Blaustein et al. 2010). Snowpack and snowmelt changes that dry or eliminate habitat can also reduce recruitment by disrupting salamander phenology, functioning, and developmental timing (Vuln. Assessment

³ 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.

⁴ Projections for changes in annual and seasonal precipitation by ecoregion can be found in the full climate impacts table (<https://bit.ly/2LHgZaG>).

Reviewer, pers. comm., 2019); increasing respiratory stress (Hillyard 1999); and causing mortality (McMenamin et al. 2008; Thomson et al. 2016).

Regional Snowpack & Snowmelt Trends	
<p><i>Historical & current trends:</i></p> <ul style="list-style-type: none"> • 15–39% decrease in April 1 snow water equivalent (SWE) between 1951 and 2010 for the Northwestern California and Southern Cascade ecoregions (Flint et al. 2013) • 15–40-day shift towards earlier date of 90% snowmelt across the western U.S. since 1915 (Hamlet et al. 2005) • 10–30-day shift towards earlier timing of snowmelt-driven runoff across the western U.S. since 1948 (Stewart et al. 2005) 	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> • Decreases in April 1 SWE by 2100 (compared to 1951–1980; Flint et al. 2013; Flint & Flint 2014): <ul style="list-style-type: none"> ○ 86–99% decrease on the North Coast ○ 82–99% decrease in the Northern Coast Range ○ 99–100% decrease in the Northern Interior Coast Range ○ 72–94% decrease in the Klamath Mountains ○ 61–89% decrease in the Southern Cascades • Likely 5–15-day shift towards earlier timing of snowmelt-driven runoff in northern California by 2100 (up to 60-day shift across the western U.S.; Stewart et al. 2004; Rauscher et al. 2008)
Summary of Potential Impacts on Species Group <i>(see text for citations)</i>	
<ul style="list-style-type: none"> • Loss or degradation of aquatic and terrestrial habitats due to hydrologic changes • Possible disruptions in salamander phenology, functioning, and developmental timing and increased risk of physiological stress and mortality 	

Streamflow

Stream and pond hydroperiod variation is a common risk factor for aquatic-breeding amphibians (Shoo et al. 2011). Reductions in water availability due to reduced snowpack and precipitation variability will likely affect the timing and magnitude of streamflows, particularly in smaller streams (Thomson et al. 2016). The southern torrent salamander is a headwater-associated species occurring in intermittent streams with discontinuous flow (Olson & Weaver 2007; Olson & Burton 2014; Olson et al. 2014). In northern California, this species is particularly vulnerable to changes in streamflow due to their narrow habitat requirements (i.e., small, high quality streams in late seral forests) and dependence on aquatic habitats at all life stages (Petranka 1998; Thomson et al. 2016; Vuln. Assessment Workshop, pers. comm., 2017). However, coastal populations may experience less extreme changes due to smaller projected precipitation changes on the coast compared to more inland sites (Thomson et al. 2016; Vuln. Assessment Workshop, pers. comm., 2017). The coastal giant salamander would likely also be severely impacted by reductions in streamflow due to their prolonged juvenile stage in coastal stream habitats (Petranka 1998; Vuln. Assessment Workshop, pers. comm., 2017), though they occur in slightly larger perennial streams compared to torrent salamanders (Olson & Weaver 2007; Olson & Burton 2014; Olson et al. 2014). Many other species dependent on aquatic habitat are likely sensitive to changes in streamflow, including the California newt (*Taricha torosa*), red-bellied newt (*T. rivularis*), rough-skinned newt (*T. granulosa*), and

northwestern salamander (Thomson et al. 2016; 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 decreased and late summer recession rates have increased over the past 40-80 years (Sawaske & Freyberg 2014; Asarian & Walker 2016; Klein et al. 2017) • September streamflow declined at 73% of undammed sites in northern California and southwest Oregon (Asarian & Walker 2016) 	<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 timing of spring peak flows (by up to 30 days; Stewart et al. 2005) • 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"> • Reduced habitat availability for species that are dependent on aquatic habitats during one or more life stages 	

Water temperature

Water temperature affects salamanders directly through increased physiological stress, reduced reproductive success, and altered larval development and indirectly through decreased food availability (Blaustein et al. 2010; Bury 2015; Thomson et al. 2016). Many salamander species are strongly associated with coldwater habitats. For example, in Humboldt County, southern torrent salamanders occur primarily in headwater streams cooler than 13.5°C (56.3°F; Welsh Jr & Hodgson 2011; Thomson et al. 2016). Warm water temperatures can cause amphibians to metamorphose earlier and at smaller sizes (Vuln. Assessment Reviewer, pers. comm., 2019), which could be detrimental because size at metamorphosis is usually positively correlated with post-metamorphic survival (Scott 1994; Searcy et al. 2014). Reduced levels of dissolved oxygen in aquatic habitats, which are associated with warmer water temperatures, may also delay development and/or hatching of salamanders, or could cause premature hatching (Blaustein et al. 2010). Finally, increased water temperatures are likely to affect the availability of spring macroinvertebrates, an important salamander food source (Durance & Ormerod 2007).

Regional Water Temperature Trends	
<p><i>Historical & current trends:</i></p> <ul style="list-style-type: none"> • ~0.1°C (0.2°F) per decade increase in mean August stream temperatures in northwestern California from 1976–2015 (Isaak et al. 2017) 	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> • 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)

Regional Water Temperature Trends	
<ul style="list-style-type: none"> ○ Corresponds to a 0.4°C (0.7°F) increase in air temperature and 5.3% decrease in discharge per decade 	<ul style="list-style-type: none"> ○ 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)
Summary of Potential Impacts on Species Group <i>(see text for citations)</i>	
<ul style="list-style-type: none"> ● Decreased reproductive success and altered larval development ● Reduced abundance of macroinvertebrate food sources 	

Drought

Drought is likely to stress salamanders directly by increasing physiological stress and mortality rates, and indirectly by affecting habitat quality in both terrestrial and aquatic systems (McMenamin et al. 2008; Price et al. 2012; Thomson et al. 2016; Grant 2018). Semi-aquatic salamanders are highly vulnerable to drought impacts, with greater impacts on larval state than on adult salamanders in some habitats (Price et al. 2012). For example, northern dusky salamander (*Desmognathus fuscus*) adults adapt to drought conditions by temporarily emigrating to new habitats, but larval mortality is high (Price et al. 2012). Periods of drought may also limit foraging and courtship activity in terrestrial habitats due to increased vulnerability to desiccation (Jaeger 1979; Grant 2018).

During drought, streamflow is significantly reduced and ponds may become ephemeral or dry earlier and more rapidly (McMenamin et al. 2008; Walls et al. 2013). Species that depend on ephemeral/intermittent and isolated aquatic habitats such as vernal pools and headwater streams are most vulnerable to drought (Rome et al. 1992). During the summer months, the loss of aquatic habitat impacts breeding salamanders (McMenamin et al. 2008), potentially resulting in reproductive failure (Blaustein et al. 2010) and/or extirpation (Walls et al. 2013). The coastal giant salamander and southern torrent salamander (Thomson et al. 2016; Vuln. Assessment Workshop, pers. comm., 2017) are especially vulnerable to hotter, drier conditions that eliminate or degrade aquatic habitat (Blaustein et al. 2010; Lawler et al. 2010).

Plant community structure and composition within aquatic and terrestrial salamander habitat is also affected by drought and associated increases in wildfire risk, which can influence reproduction and recruitment (Blaustein et al. 2010; Vuln. Assessment Reviewer, pers. comm., 2019). Loss of canopy cover and changes in vegetation as a result of drought can alter microclimatic factors, such as light, temperature, and moisture, as well as the accumulation, quality, and decomposition of the leaf litter that salamanders depend on to retain soil moisture and provide cover from predators (Petranka 1998; Kloeppel et al. 2003).

Regional Drought Trends	
<p><i>Historical & current trends:</i></p> <ul style="list-style-type: none"> • 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"> • 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 <i>(see text for citations)</i>	
<ul style="list-style-type: none"> • Altered behavior patterns and reduced fitness during periods of drought • Decreased quality and availability of aquatic habitat, likely resulting in reduced reproductive success in stream and pond-breeding salamanders 	

Air temperature and heat waves

Increases in air temperature are likely to affect salamanders directly by increasing thermal stress and desiccation, particularly during periods of reduced precipitation (Bogaerts 2004; Thomson et al. 2016). Salamander phenology (e.g. reproduction, foraging, estivation) may also be impacted by warmer temperatures, which are associated with reduced activity (Vuln. Assessment Reviewer, pers. comm., 2019). *Plethodontid* salamanders that rely heavily on cutaneous respiration are particularly vulnerable to warmer temperatures that increase the rate of evaporative water loss across their skin (Bogaerts 2004). Salamander species differ in their air temperature tolerance levels, but at very high temperatures salamanders may secrete mucous, seek cooler locations, lose coordination, become paralyzed, or die (Bogaerts 2004). Some salamanders appear to develop a tolerance for warm temperatures if they increase gradually (Bogaerts 2004). Air temperature, especially when combined with reduced precipitation, may also contribute to the loss or degradation of sensitive salamander habitats (e.g., ephemeral ponds), causing salamander population declines or local extirpations (Blaustein et al. 2010).

Over the longer term, salamanders may adapt to warmer air temperatures through a reduction in body size, either through plasticity in growth response or changes in physiological response to energy allocation as hotter, drier weather causes salamanders to burn energy faster (Caruso et al. 2014). Studies from the 1950s to 2012 have shown that several *plethodontid* salamander species are now smaller in size, consistent with a plastic response of body size to climate change (Caruso et al. 2014). However, this response is unlikely to stop population losses from climate stressors that affect multiple parts of a species' life history (Vuln. Assessment Reviewer, pers. comm., 2019).

Regional Air Temperature & Heat Wave Trends	
<p><i>Historical & current trends:</i></p> <ul style="list-style-type: none"> • 0.03°C (0.05°F) decrease to 0.5°C (0.9°F) increase in the average annual temperature between 1900 and 2009 for the Northwestern California, Southern Cascade, and Great Valley ecoregions (Rapacciuolo et al. 2014) <ul style="list-style-type: none"> ○ No seasonal temperature trends available • 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"> • 2.2–6.1°C (4.0–11.0°F) increase in the average annual temperature 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) <ul style="list-style-type: none"> ○ 1.9–5.8°C (3.4–10.4°F) increase in average winter minimum temperatures ○ 2.0–6.8°C (3.6–12.2°F) increase in average summer maximum temperatures • 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"> • Loss or degradation of habitat, potentially contributing to populations declines • Increased mortality due to physiological stress 	

Sensitivity and future exposure to changes in natural disturbance regimes

Regional experts evaluated salamanders as having moderate-high sensitivity to changes in natural disturbance regimes (low confidence in evaluation), with an overall moderate-high future exposure to these stressors within the study region (moderate confidence). Key natural disturbance regimes that affect salamanders include wildfire, disease, and flooding.⁵

Wildfire

Direct impacts of wildfire and post-fire debris flows on salamanders can include mortality within both terrestrial and aquatic habitats (Hossack & Pilliod 2011). Indirectly, wildfire and post-fire events (flooding, landslides, debris flows) primarily affect salamanders through alteration of terrestrial and aquatic habitats, with the impacts varying across habitats and spatial scales (Hossack & Pilliod 2011). Individual salamanders or small populations may respond to disturbances at the microhabitat level, where fires eliminate or alter cover through burning of understory vegetation and woody debris or deposit ash and sediment in aquatic substrates (Hossack & Pilliod 2011). At the macrohabitat level (e.g. forest, stream), fires may increase solar radiation and water temperatures, alter forest microclimates and hydroperiods in aquatic habitat, and enhance productivity in aquatic systems (Hossack & Pilliod 2011).

⁵ All disturbance regimes presented were ranked as having a moderate or higher impact on this species group.

In general, species with a limited distribution (e.g., *Hydromantes* spp.), dependence on restricted microclimate associations, and limited capacity for recolonization are likely to be most affected by altered wildfire regimes (Pilliod et al. 2003; Hossack & Pilliod 2011). In addition, the sensitivity of salamanders to wildfire likely varies among life stages, populations in different geographic regions, and species, depending on life history characteristics (e.g., reproduction timing, larval period duration, adult mobility, and desiccation resistance; Pilliod et al. 2003). For instance, species with biphasic life cycles (e.g., southern torrent salamander) could be somewhat insulated from significant losses following wildfire in one habitat type (e.g., aquatic larvae die but terrestrial adults survive; Hossack & Pilliod 2011). *Plethodontid* salamanders also exhibit burrowing behavior during the summer months that can buffer them from the direct effects of wildfire during the period when fires are most likely to occur (Hossack & Pilliod 2011).

Aquatic habitats

Wildfire may cause significant changes in the structure and function of aquatic habitats (Corn et al. 2003; Dunham et al. 2007), particularly in smaller pools where changes in water quality (e.g., increased nitrogen and phosphorus) can have significant impacts on aquatic food webs (Batzer et al. 2000; Palik et al. 2001; Vuln. Assessment Workshop, pers. comm., 2017). Rapid increases in water temperatures can also occur during wildfire from fuel combustion or post-fire from increased solar radiation due to the loss of riparian vegetation (Minshall et al. 1997; Hossack & Pilliod 2011). Post-fire debris flows can reduce breeding habitat by filling pools and stream channels with sediment and debris (Hossack & Pilliod 2011; Norgaard et al. 2016), and pools that do not fill completely may still become shallower and more likely to dry before larvae can metamorphose (Sredl & Wallace 2000). However, over longer time scales the introduction of sediment and debris into streams can increase habitat complexity and enhance aquatic food production (Pilliod et al. 2003; Norgaard et al. 2016), which could improve foraging opportunities for salamanders. Reduced forest density following fire also increases the amount of runoff available for streamflow, potentially enhancing aquatic habitat (Pettit & Naiman 2007; Tague et al. 2009).

Terrestrial habitats

Low-intensity fires, such as occurs during prescribed or cultural burning, typically do not have significant effects on terrestrial salamander populations (Major 2005; Bagne & Purcell 2009; Norgaard et al. 2016; Karuk Tribe 2019), likely because patches of leaf litter and woody debris remain and overstory canopy closure is unaffected (Bagne & Purcell 2009). Wildfire can also increase recruitment of coarse woody debris to the forest floor (Major 2005; Lindenmayer & Noss 2006). Pockets of lower-intensity fire may provide critical refugia for salamanders that can later recolonize nearby areas burned at higher intensity (Hossack & Pilliod 2011).

Higher-intensity fire is more likely to cause direct and the loss of prey and shelter (woody material; Bury et al. 2002; Norgaard et al. 2016). The loss of forest canopy can result in altered forest microclimates (i.e., reduced humidity, increased temperatures; Cummer & Painter 2007) and the loss of moist microsites utilized by salamanders (Norgaard et al. 2016). High-intensity

fires can also make soil hydrophobic for a period of time, reducing moisture storage capacity and increasing the risk of severe erosion and debris flows (Doerr et al. 2000; Mao et al. 2019).

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 highest values occurring after 2000 (Miller et al. 2012) • 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 	<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) ○ 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"> ○ Adult mortality in terrestrial upland habitats ○ Reduced prey availability and decreased habitat quality in terrestrial upland habitats affected by severe fire, including alterations to microhabitats that could affect survivability • <i>Short-term (~2-year):</i> <ul style="list-style-type: none"> ○ Upland habitat degradation due to drier microclimates in areas where forest canopy was lost ○ Increased downed wood following low- to moderate-severity fires 	

Regional Wildfire Trends
<ul style="list-style-type: none"> ○ Possible increases in aquatic productivity, which could improve foraging opportunities ○ Loss or degradation of aquatic and riparian habitats following post-fire debris flows ● <i>Long-term:</i> <ul style="list-style-type: none"> ○ Possible expansion of aquatic habitat due to increased water yield following reduction of forest density

Disease

Like other amphibians, salamanders in northern California are affected by the introduced pathogenic chytrid fungus (*Batrachochytrium dendrobatidis*, Bd; Weinstein 2009; Sette et al. 2015), which originated in Asia and has spread globally (O’Hanlon et al. 2018). A newly described chytrid species (*B. salamandrivorans*; Bsal) from Asia also appears to cause disease in some salamander species, warranting additional concern in northern California (Martel et al. 2013, 2014; Yap et al. 2015; Richgels et al. 2016; North American Bsal Task Force 2019). These pathogens can cause effects ranging from disease tolerance to death in infected salamanders depending on factors including host susceptibility, fungal virulence, and environmental variables (Van Rooij et al. 2015). Both chytrid fungi can be carried by disease-tolerant host species, some of which are highly invasive such as the African clawed frog (*Xenopus laevis*; Vredenburg et al. 2013) and the American bullfrog (*Rana catesbeiana*; Huss et al. 2013), as well as by the native Pacific chorus frog (*Pseudacris regilla*; Reeder et al. 2012) and species common in trade markets (e.g., Bsal in Chinese fire-bellied newts [*Cynops orientalis*]; Yuan et al. 2018).

Aquatic species are particularly vulnerable to infection because fungal zoospores are transmitted readily in water but become desiccated rapidly on land (Piotrowski et al. 2004). Terrestrial species with a higher degree of sociality are also more vulnerable due to increased disease transmission (Sette et al. 2015). Salamander declines due to chytridiomycosis appear to be driven by the interaction between increasing temperatures and disease, and salamander species adapted to cooler environments are likely to be most vulnerable to the disease as air temperatures continue to increase (Cohen et al. 2019). This may be partly because environmental stress due to climate change can compromise the immune system, increasing susceptibility to infection and survival (Rollins-Smith 2017). Altered precipitation patterns are also likely to impact fungal reproduction and transmission (Weinstein 2009).

Regional Disease Trends	
<p><i>Historical & current trends:</i></p> <ul style="list-style-type: none"> ● No trends available for disease 	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> ● Increased disease risk (e.g., chytridiomycosis) due to warmer temperatures and changes in precipitation that impact patterns of disease prevalence as well as susceptibility in stressed individuals (Pounds et al. 2006; Sette et al. 2015)

Regional Disease Trends	
	<ul style="list-style-type: none"> Expansion of the projected future climate niche for <i>Bd</i> in northern temperate ecosystems (Xie et al. 2016)
Summary of Potential Impacts on Species Group (see text for citations)	
<ul style="list-style-type: none"> Increased illness and mortality, particularly in stressed individuals 	

Flooding

In both aquatic and terrestrial habitats, flooding can damage the physical environment (e.g., by removing cover), increase populations of potential competitors and predators, and/or cause direct salamander mortality (Palis 1996; Deitloff 2011). For instance, flooding can introduce fishes (salamander predators) into normally isolated, fishless wetlands (Palis 1996). Following a fire, flooding and landslides can deposit large woody debris into streams, but increased peak flows, erosion, and decreased bank stability can also remove large amounts of instream wood (Young 1994; Minshall et al. 1997). In low-elevation aquatic habitats, frequent flooding likely facilitates moderate to high gene flow by dispersing adult and larval salamanders to new habitats during the breeding season (Giordano et al. 2007). However, severe flooding can eliminate large numbers of young larval salamanders, while reducing competition for resources for those that survive (Petranka & Sih 1986). Flooding can also destroy/dislodge egg masses in side channels and stream oxbows (Vuln. Assessment Reviewer, pers. comm., 2019).

Large landslides and debris flows associated with heavy precipitation and flooding can also cause significant mortality. For instance, genetic data of coastal giant salamanders has showed evidence of population bottlenecks that could be consistent with episodic mortality events such as a headwater failure that scours a drainage (Vuln. Assessment Reviewer, pers. comm., 2019).

Regional Flooding Trends	
<p><i>Historical & current trends:</i></p> <ul style="list-style-type: none"> No trends available for flooding 	<p><i>Projected future trends:</i></p> <ul style="list-style-type: none"> More frequent/severe winter flooding due to an increase in extreme precipitation events (Dettinger 2011; AghaKouchak et al. 2018; Swain et al. 2018; Grantham et al. 2018) State-wide, 200-year floods are expected to increase in frequency by 300–400%, becoming 50-year floods (Swain et al. 2018)
Summary of Potential Impacts on Species Group (see text for citations)	
<ul style="list-style-type: none"> Reduced habitat quality, including the removal of cover and/or deposition of sediment and debris Introduction of potential competitors and predators into salamander habitat Increased salamander mortality, particularly among larval salamanders 	

Dependency on habitat and/or other species

Regional experts evaluated salamanders as having high dependency on sensitive habitats (high confidence in evaluation) and low-moderate dependency on prey or forage species (low confidence).

In northern California, salamanders are dependent on a variety of habitats and microhabitat conditions for survival and reproduction (Petranka 1998; Thomson et al. 2016). Salamanders that breed in aquatic habitats often occur in riparian or moist forests and near cold creeks, rivers, streams, lakes, and ponds (McComb et al. 1993; Welsh & Lind 1996; Petranka 1998). In general, stream-specialist salamanders require small, cold, and clear (often headwater) streams (Petranka 1998). Terrestrial species require deep leaf litter, coarse woody debris, and, for some species, rock crevices and talus slopes (e.g., Petranka 1998; Kluber et al. 2009). Some terrestrial and semi-aquatic species are strongly associated with late-seral forests (Blaustein et al. 1995; Petranka 1998; Olson et al. 2009). All salamanders that occupy terrestrial habitat for part or all of the year also require sufficient moisture to hydrate their highly permeable skin and adequate leaf litter for use as foraging grounds (Blaustein et al. 2010). All are also dependent on habitats that provide healthy macroinvertebrate populations as prey, though some species also prey on small mammals (Bury 2004; Thomson et al. 2016).

Sensitivity and current exposure to non-climate stressors

Regional experts evaluated salamanders as having moderate-high sensitivity to non-climate stressors (moderate confidence in evaluation), with an overall moderate current exposure to these stressors within the study region (low confidence). Key non-climate stressors that affect salamanders include dams and water diversions, residential and commercial development, pollution and poisons, fire suppression, timber harvest, and invasive species.⁶

Dams and water diversions

Dams can create impoundments that eliminate salamander habitat, especially for semi-aquatic species (Thomson et al. 2016). Water diversions and culverts can disturb salamander habitat and reduce reproduction by modifying water velocity and the hydrological processes affecting sediment transport and bedload (Sagar et al. 2007). Water diversions, which often occur in headwater streams, are of particular concern for the southern torrent salamander, which has been observed to occur above but not below such diversions (Thomson et al. 2016).

Cannabis (*Cannabis sativa* or *C. indica*) production, in particular, is a major source of water diversion in salamander habitat in northern California (Bauer et al. 2015). Some watersheds on the North Coast have had up to 100% of their flow withdrawn during the summer growing season (Bauer et al. 2015). In some areas, growers may also dig out seeps and springs, permanently altering their hydrology (Vuln. Assessment Reviewer, pers. comm., 2019).

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 energy production/mining, and roads/highways/trails.

Residential and commercial development

Land use and development (e.g., residential housing, vineyards, cannabis production) degrades, eliminates, and fragments salamander habitat. Land development can prevent successful dispersal of juveniles across habitats and result in substantial reductions in post-metamorphic survival, reducing population connectivity and viability (Cushman 2006). Development also reduces canopy cover and causes shifts in vegetation composition, which may alter temperature and moisture levels and affect the accumulation and decomposition of leaf litter that provides important salamander microhabitat (Blaustein et al. 2010). Cannabis cultivation, including grading, roadbuilding, and application of herbicides and pesticides, can negatively impact salamanders and their habitat (Thompson et al. 2014; Thomson et al. 2016). Pressure on salamander habitat from rural development is likely to increase on most of the privately-owned lands in the region as the wildland-urban interface expands and remote parcels are increasingly subdivided (Vuln. Assessment Reviewer, pers. comm., 2019).

Pollution and poisons

Salamanders are highly sensitive to pollutants that enter their habitat through both overland and aquatic pathways, including pesticides (Ryan et al. 2013), herbicides (Rohr & Palmer 2005), and chemical applications commonly used for fire suppression (Pilliod et al. 2003; Norgaard et al. 2016) or road maintenance (Karraker & Gibbs 2011). Salamanders may also be affected by leaching in mined areas, which can introduce mercury and other heavy metals into aquatic habitats (Vuln. Assessment Reviewer, pers. comm., 2019). Pollutants can affect salamanders by disrupting embryo development and reducing invertebrate prey availability, causing larval mortality (Ryan et al. 2013). The loss of invertebrate prey likely harms adults as well, particularly in species where the adults live in more aquatic habitats (e.g., newts; Vuln. Assessment Reviewer, pers. comm., 2019). Roads and trails introduce pollutants and contaminants to nearby aquatic habitats (Sagar et al. 2007), and aquatic breeding sites also can be acidified by weathering of rocks cut for road building and mining (Petranka 1998).

Fire exclusion and suppression

Fire exclusion can enhance the risk of high-severity fire in forests and riparian habitats by increasing fuel availability (Dwire & Kauffman 2003; Norgaard et al. 2016), with potential negative impacts on salamander habitat suitability (see Table 1; Bury et al. 2002; Pilliod et al. 2003). Fire retardant chemicals used to suppress fires can cause salamander mortality (Pilliod et al. 2003; Norgaard et al. 2016). Fire suppression activities such as fuel break construction also have the potential to fragment salamander habitat (Vuln. Assessment Reviewer, pers. comm., 2019).

Table 1. Impacts of fire exclusion/suppression on the resilience of salamanders to climate stressors and climate-driven changes in fire regimes (table adapted from Norgaard et al. 2016).

Prior to Fire	During Fire	After Fire
<ul style="list-style-type: none"> Increased risk of high-severity fire in riparian habitats due to fuel loading 	<ul style="list-style-type: none"> Possible mortality due to introduction of toxins present in some fire-retardant chemicals 	<ul style="list-style-type: none"> Reduced habitat suitability in riparian areas burned at high severity
Source(s): Bury et al. 2002; Dwire & Kauffman 2003; Pilliod et al. 2003		

Timber harvest

Historical timber harvesting practices did not consider broader ecosystem effects and have largely resulted in long-term, wide-ranging legacy impacts on salamander survival (Marsh & Beckman 2004; Karraker & Welsh 2006; Semlitsch et al. 2009) and population connectivity (Petranka 1998; Cushman 2006; Thomson et al. 2016). Practices such as historical clear-cutting killed salamanders by crushing them with heavy equipment as well as eliminating shading and leaf litter, increasing soil surface temperature, and reducing leaf litter moisture (DeMaynadier & Hunter 1995; Welsh & Droege 2001; Welsh & Hodgson 2008). The loss of these microhabitats increases physiological stress on salamanders because they rely on their moist skin as a respiratory organ (DeMaynadier & Hunter 1995). In riparian areas, the loss of the tree canopy after clear-cutting increases water temperatures, potentially reducing habitat for cold-adapted salamanders (Thomson et al. 2016). Such timber harvesting methods also have had negative impacts on genetic diversity by creating barriers to salamander movement across the landscape (Miller et al. 2006; Emel et al. 2019). For instance, the coastal giant salamander has shown lower levels of genetic variation in areas of recent clear-cuts, suggesting reduced population sizes and densities (Curtis & Taylor 2004).

Some timber harvesting approaches can alter salamander behavior regarding habitat use. For instance, coastal giant salamanders tend to remain closer to streams, spend more time in subterranean refuges, and have smaller home ranges in areas of clear-cuts than in forested habitat (Johnston & Frid 2002). Some salamander species can better mediate the impacts of logging in milder and wetter habitats near the coast (Welsh 1990; Diller & Wallace 1996). More recent developments in forest density management and variable density harvest practices may ameliorate negative effects on terrestrial salamanders (Rundio & Olson 2007; Kluber et al. 2009). Retention of riparian buffers are also proving successful at retaining stream-riparian forest salamander species persistence and instream habitat conditions (e.g., Olson & Rugger 2007; Rundio & Olson 2007; Olson & Burton 2014; Olson et al. 2014).

Invasive species

Numerous aquatic invasive species are documented in northern California aquatic habitats in and adjoining ecoregions (Olson & Flitcroft 2018). In northern California, aquatic-breeding salamanders are negatively impacted by non-native fish and the American bullfrog, which increase competition or predation risk for salamanders (Welsh et al. 2006; Fuller 2008; Elliott et al. 2009). Although bullfrogs are currently restricted to low- and mid-elevation habitats,

warmer temperatures may allow their ranges to expand to higher elevations (Fuller 2008). Additionally, the loss of ephemeral habitats at higher elevations associated with drier conditions may also increase predation risk for native pond-breeding salamanders if they need to rely more heavily on permanent aquatic habitats where bullfrogs are found (Vuln. Assessment Reviewer, pers. comm., 2019). American bullfrogs can also be a vector that spreads the fungal pathogen *Bd* (Huss et al. 2013; Sette et al. 2015).

Introduced species of non-native fish prey on eggs and larval salamanders, reducing populations (Gamradt & Kats 1996; Ryan et al. 2014). Introduced fish may also assume the role of apex predator in previously fishless lakes (Tyler et al. 1998; Elliott et al. 2009). For instance, the larval stage of the long-toed salamander, a top predator in high-elevation fishless lakes, decrease when lakes are stocked with trout, likely due to predation (Tyler et al. 1998; Welsh et al. 2006). Funk & Dunlap (1999) also found that the presence of trout effectively excluded long-toed salamander populations from lakes; however, salamanders recolonized lakes after the extinction of trout populations. Introduced crayfish (*Procambarus clarkii*) are also known to eat the larvae and egg masses of California newts, which are less likely to exist in streams that contain crayfish (Gamradt & Kats 1996).

In upland habitats, invasive wild turkeys (*Meleagris gallopavo*) and feral pigs (*Sus scrofa*) can reduce habitat quality and eat terrestrial salamanders (Vuln. Assessment Reviewer, pers. comm., 2019).

Adaptive Capacity

Salamanders were evaluated by regional experts as having low-moderate overall adaptive capacity (low confidence in evaluation).

Species group extent, integrity, connectivity, and dispersal ability

Regional experts evaluated salamanders as having a low-moderate geographic extent (high confidence in evaluation), moderate overall health and functional integrity (low confidence), and a low-moderate degree of connectivity between populations (low confidence).

In northern California, many salamander species are widely but patchily spread across the landscape, while others are restricted to very small ranges (Nussbaum et al. 1983; Petranka 1998; Thomson et al. 2016). For instance, the suite of three species of endemic Shasta salamanders (*Hydromantes spp.*) is found only within a limited area near Shasta Lake (Nauman & Olson 2004; Bingham et al. 2018), and the Siskiyou Mountains salamander is limited to a small range in the Siskiyou Mountains (Olson et al. 2009).

Globally, 43% of amphibian species are experiencing population declines (Stuart et al. 2004), and declines in salamander species are part of this larger trend (Wake & Vredenburg 2008; Elliott et al. 2009; Thomson et al. 2016). Major declines have been documented in the abundance and range of many California species; for example, the current range of many

salamander populations has been reduced by habitat loss and fragmentation as a result of development, timber harvesting, and disease, among other factors (Blaustein et al. 2010; Hof et al. 2011; Thomson et al. 2016). Climate change is expected to further accelerate abundance and range losses of amphibian species (Thomson et al. 2016).

Regional experts evaluated salamanders as having a low dispersal ability (moderate confidence in evaluation). Barriers to dispersal were evaluated as having a moderate impact on the species group (moderate confidence). Land-use conversion, agriculture, roads/highways/trails, dams and water diversions, invasive species, timber harvest and clear-cuts, and geologic features were identified as the primary barriers to dispersal.⁷ These factors may prevent dispersal and successful recolonization of areas from which salamanders may have been extirpated (e.g., by distance or stressors such as wildfire, timber harvesting, water diversion, or disease; Thomson et al. 2016). The dispersal ability of salamanders is likely to be particularly limited by the practice of forest clear-cutting, as most species will not disperse any appreciable distance across non-forested habitat (Cushman 2006; Emel et al. 2019). The disappearance of some springs in a warmer, drier climate may also increase habitat fragmentation (Vuln. Assessment Reviewer, pers. comm., 2019).

Mark-recapture studies and landscape genetics studies of gene flow patterns can offer insights to salamander movements and dispersal, but few studies of this nature have been investigated for salamanders in northern California. Known movement and dispersal distances range widely depending on species, available cover, distance to streams, and other factors (Johnston & Frid 2002; Kluber et al. 2008; Emel et al. 2019). For instance, Hendrickson (1954) reported limited movement of only 1.5 m (5 ft) for the California slender salamander. By contrast, a summary of movement in Pacific Northwest salamanders by Olson et al. (2007) reported that salamanders captured away from streams (a measure of movement capability in stream-breeding salamanders) were found at maximum distances of 400 m for *D. tenebrosus* and 200 m for *Rhyacotriton* species (McComb et al. 1993; Gomez & Anthony 1996). Forest management can play a significant role in determining the movement and dispersal of some species. For instance, a study in British Columbia found that *D. tenebrosus* in clearcuts remained closer to streams, spent more time underground, and had smaller home ranges, whereas movements of salamanders in riparian buffer strips appeared similar to forested stands (Johnston & Frid 2002). Olson and Kluber (2014) found a pattern of greater *plethodontid* movements among cover boards within 15 m of streams, and hypothesized that streamside riparian areas were functioning as critical habitat for some terrestrial salamanders due to their cool, moist microclimates (Anderson et al. 2007; Rykken et al. 2007), and were likely dispersal conduits. Override connectivity pathways linking headwater streams in distinct adjacent watersheds have also been modeled, showing potential dispersal routes and considerations for land management for species connectivity corridors (Olson & Burnett 2009, 2013). Using landscape genetics, Emel et al. (2019) confirmed gene flow of *Rhyacotriton* species across such ridgelines, with forest cover being a top predictor of gene flow among sites. Preliminary data for

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 energy production and mining.

Dicamptodon tenebrosus also confirms override connectivity of populations in neighboring watersheds (D. Olson, pers. comm., 2019).

Intraspecific/life history diversity

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

Northern California salamanders demonstrate some diversity in life history strategies and behavioral/phenotypic plasticity, which likely evolved as adaptations to the wide range of habitats and climates they occupy (Welsh 1990; Petranka 1998; Thomson et al. 2016). Salamanders are able to move between habitat niches in response to local environmental stressors, providing them with some ability to mitigate the impacts of increasing stressors or disturbances (Welsh 1990; Diller & Wallace 1996). For instance, salamanders are known to retreat underground to avoid the impacts of high temperatures or short-term drought (Grant 2018), or move to cooler aquatic refuge (Humphries & Baldwin 2003; Lake 2003) or thermally-buffered talus slopes (Vuln. Assessment Reviewer, pers. comm., 2019). Terrestrial *plethodontid* salamanders can also delay egg-laying by several months in response to unfavorable environmental conditions (Petranka 1998). Over the longer-term, salamanders may adjust to warmer temperatures or shorter active seasons by decreasing body size, either through plasticity in growth response or changes in physiological response (i.e., energy allocation; Caruso et al. 2014; Grant 2018). *Plethodontid* salamander species have already demonstrated significant reductions in body size from the 1950s to 2012 as mediated through increased metabolism, consistent with a plastic response of body size to climate change (Caruso et al. 2014). However, this response is unlikely to stop population losses due to climate changes that affect multiple parts of a species' life history (Vuln. Assessment Reviewer, pers. comm., 2019).

Genetic diversity of salamanders varies among species (Giordano et al. 2007; Thomson et al. 2016), and can be extremely high for some species complexes (e.g., black salamanders; Reilly et al. 2012). Habitat elevation and topography influence genetic diversity within species by limiting dispersal across high ridges and other barriers (Giordano et al. 2007; Reilly et al. 2013). For instance, the southern long-toed salamander occurs in a larger variety of habitat types than any other salamander in the northwestern United States (Ferguson 1961; Nussbaum et al. 1983), including arid grassland and sagebrush communities, dry woodlands, coniferous forests, alpine meadows, and a wide variety of intermediate habitat types (Ferguson 1961; Petranka 1998; Pilliod & Fronzuto 2005). This species appears to be genetically differentiated at lower and higher elevation sites, and at higher elevation sites may have less genetic diversity due to lower connectivity and gene flow among sites (Giordano et al. 2007). Lack of habitat connectivity also plays a role in low genetic diversity for the southern torrent salamander in isolated pockets of vegetation (Petranka 1998; Emel & Storfer 2015). Because these salamanders rarely migrate long distances, small, isolated populations are at greater risk of low genetic diversity, increasing their vulnerability to stressors and disturbances in a changing climate (Giordano et al. 2007; Savage et al. 2010). Some species such as the black salamander

appear to comprise many Evolutionary Significant Units and/or species-level units, and a lack of knowledge about conservation genetics limits effective management of many species (Reilly et al. 2012; Reilly & Wake 2015).

Resistance and recovery

Regional experts evaluated salamanders as having low-moderate resistance to climate stressors and natural disturbance regimes (moderate confidence in evaluation). Recovery potential was evaluated as low-moderate (low confidence).

Like many amphibians worldwide (Stuart et al. 2004; Wake & Vredenburg 2008), salamanders in California are declining due to climate change and habitat development and fragmentation (Thomson et al. 2016). Little demographic information exists to demonstrate recovery potential of these species (Vuln. Assessment Workshop, pers. comm., 2017). However, longer-lived species may be resilient to occasional periods of climate extremes. Similarly, species with greater fecundity may have more chances at surviving ‘bust years’ due to adverse conditions (Vuln. Assessment Reviewer, pers. comm., 2019).

The limited ability of salamanders to disperse overland to new habitats reduces their ability to recover from localized disturbances that are likely to increase with climate change, including high-intensity wildfire and drying of habitat from increased air temperatures and hydrological changes (Petranka 1998; Thomson et al. 2016). In northern California, salamanders have adapted to habitat variability and environmental change through differing life history traits, behavioral plasticity, and physiological responses (Petranka 1998; Thomson et al. 2016). For example, the physiological response of skin shedding may be an important survival mechanism for salamanders against disease (Weinstein 2009), and salamanders may increase movements to cooler aquatic microrefugia in response to hydrologic changes in stream and pond habitats (Humphries & Baldwin 2003; Lake 2003). Species with greater dispersal ability may be better able to traverse landscapes to reach climate refugia in response to thermal and hydrologic changes such as these (Vuln. Assessment Reviewer, pers. comm., 2019).

Management potential

Public and societal value

Regional experts evaluated salamanders as having moderate public and societal value (low confidence in evaluation).

Despite their widespread distribution, salamanders are one of the least understood North American vertebrates due in part to their cryptic behavior (Petranka 1998), and there is limited public understanding of the threats facing salamanders (Vuln. Assessment Workshop, pers. comm. 2017). Multiple salamander species (e.g., southern torrent salamander, southern long-toed salamander) are identified as conservation targets in the California State Wildlife Action Plan 2015 Update (CDFW 2015), several of which are also identified as federally sensitive species (CDFW 2019). However, funding and other resources for salamander conservation are much less than for similarly at-risk birds and mammals (Vuln. Assessment Reviewer, pers.

comm., 2019). There are some existing regulations to limit the effects of stressors on salamanders, including hunting, collecting, and timber harvest on stream-breeding species (Vuln. Assessment Workshop, pers. comm., 2017), and catastrophic events, such as high-severity wildfires or prolonged droughts, would likely increase public awareness of and support for salamander conservation (Vuln. Assessment Workshop, pers. comm., 2017).

Management capacity and ability to alleviate impacts⁸

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

The scientific literature suggests multiple approaches to protect salamanders and their habitats from changing stressors and disturbance regimes (Shoo et al. 2011). Many of these strategies focus on reducing habitat degradation and loss associated with non-climate stressors such as timber harvest. For instance, intensive management and harvesting techniques such as clear-cutting and plantation forestry have significant adverse impacts on salamanders (DeMaynadier & Hunter 1995). Healthy populations of salamanders can be maintained by using partial harvest techniques and long-term rotation cycles, in combination with the protection of mature forests that provide optimal habitat (DeMaynadier & Hunter 1995). These protected areas should include core habitats within riparian zones utilized by breeding amphibians, with recommended buffer widths varying depending on upland harvest strategies (DeMaynadier & Hunter 1995; Semlitsch & Bodie 2003; Olson et al. 2007; Olson 2015; Reeves et al. 2018). These buffers may maintain populations and allow corridors for repopulation once forest regeneration has created suitable habitat in harvested uplands (Bury & Corn 1988a; Olson & Burnett 2009, 2013; Olson & Kluber 2014). Other salamander habitats that could be prioritized for protection include springs, seeps, and other headwater habitats (Petranka 1998); large rock outcrops; talus slopes; ponds; and unique patches of habitat that are critical to certain highly sensitive species (e.g., Del Norte salamander; Bury & Corn 1988b; Herrington 1988). However, these strategies may not sufficiently guard salamanders from the negative impacts of climate change due to their high sensitivity to desiccation (Vuln. Assessment Reviewer, pers. comm., 2019).

Maintaining moist microsites in upland habitats is critical, and managers should consider leaving downed wood on the forest floor for terrestrial salamanders, as well as preserving canopy cover to prevent soil drying and the alteration of understory vegetation (Welsh & Lind 1991; Olson & Burnett 2009, 2013; Shoo et al. 2011). Prescribed burning activities (including cultural burning practices; e.g., see Table 2) should be managed to minimize the risk of adult mortality, while maximizing the potential benefits of fire for aquatic and riparian systems (Bury et al. 2002; Dwire & Kauffman 2003; Norgaard et al. 2016; Karuk Tribe 2019). Other strategies that could minimize stress include minimizing disease spread by limiting pathogen introduction and promoting early detection through surveillance of high-risk areas (Richgels et al. 2016).

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

Table 2. Effects of prescribed fire on salamanders across time (table adapted from Norgaard et al. 2016). Cultural burning practices, in particular, have played a role in maintaining these species on the landscape over very long time scales.

Immediate	2-Year	Long Term
<ul style="list-style-type: none"> • Cultural burning takes the salamander life cycle into account and avoids burning while salamanders are most vulnerable to mortality from fire 	<ul style="list-style-type: none"> • Increased stream productivity following fire • Recruitment of woody material from dead trees to aquatic and riparian systems 	<ul style="list-style-type: none"> • Increased temporal and spatial complexity in upland habitats • Reduced risk of high-severity fire
Source(s): Bury et al. 2002; Dwire & Kauffman 2003; Perry et al. 2011; Norgaard et al. 2016; Karuk Tribe 2019		

Given the lack of data on amphibians, it will also be necessary to fill key research gaps on salamander ecology, distribution, genetics, and response to stressors/adaptation ability (Pilliod et al. 2003; Thomson et al. 2016; Vuln. Assessment Reviewer, pers. comm., 2019). For instance, research suggests that several species complexes (e.g., black salamanders, southern torrent salamanders) have very high genetic diversity and may represent multiple species (Miller et al. 2006; Olson et al. 2009; Reilly et al. 2012), but our lack of knowledge about these species creates a management challenge (Vuln. Assessment Reviewer, pers. comm., 2019). Thomson et al. (2016) suggest that California launch a program that funds and synthesizes peer-review analyses of basic ecology combined with long-term monitoring studies to evaluate demographic trends at a set of sites for each species. Other research could include investigating the effects of wildfire on salamanders in cold headwater streams (Corn et al. 2003; Hossack & Pilliod 2011).

Ecosystem services

Salamanders play an important ecological role in both terrestrial and aquatic habitats as predators of invertebrates and small mammals (Bury 1972; Burton & Likens 1975; Best & Welsh 2014), inhabiting an essential trophic level in the ecosystem in which leaf litter and invertebrate biomass is converted to vertebrate biomass far more efficiently than by birds and mammals (Pough 1980; Welsh & Lind 1992; Best & Welsh 2014). In turn, salamanders provide food for a variety of fish, snakes, small mammals, woodland birds and herons, and invertebrates (Petranka 1998; Davic & Welsh 2004). For example, these small vertebrates inhabit an essential trophic level in the ecosystem in which leaf litter and invertebrate biomass is converted to vertebrate biomass far more efficiently than by birds and mammals (Pough 1980; Welsh & Lind 1992; Best & Welsh 2014). Aquatic-larval salamanders that transform to terrestrial adults also have a key functional role in transferring energetic subsidies from aquatic systems to uplands, and vice versa (reciprocal subsidies; (Baxter et al. 2005; Semlitsch et al. 2014). In addition, salamanders have many bioactive compounds in their skin, and they play important roles in nutrient cycling (Burton & Likens 1975; Semlitsch et al. 2014). Salamanders also provide an important service to humans as a biosentinel of ecosystem health and integrity (Petranka 1998; Davic & Welsh 2004).

In addition to ecological values, the coastal giant salamander is a culturally significant indicator species for northern California tribes (Norgaard et al. 2016; Karuk Tribe 2019). For Karuk cultural practitioners, the presence of dead or dying salamanders indicates critically high water temperatures and imminent system collapse (Karuk Tribe 2019). In traditional Karuk culture, the coastal giant salamander is considered a spiritual being who transforms into a salamander to monitor water quality (Norgaard et al. 2016; Karuk Tribe 2019). Similar spiritual values of salamanders are echoed in other Northwest tribes, for example the Squamish Nation in British Columbia, Canada ascribes healing powers to salamanders, and has designated a stream reserve area as a “high spiritual value area” for salamanders (Olson 2014).

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

Literature Cited

- AghaKouchak A, Ragno E, Love C, Moftakhari H. 2018. Projected changes in California’s precipitation intensity-frequency curves. California’s Fourth Climate Change Assessment. Publication Number: CCCA4-CEC-2018-005. California Energy Commission, Sacramento, CA.
- Anderson PD, Larson DJ, Chan SS. 2007. Riparian buffer and density management influences on microclimate of young headwater forests of western Oregon. *Forest Science* **53**:254–269.
- Asarian JE, Walker JD. 2016. Long-term trends in streamflow and precipitation in northwest California and southwest Oregon, 1953-2012. *Journal of the American Water Resources Association* **52**:241–261.
- Bagne KE, Purcell KL. 2009. Response of two terrestrial salamander species to spring burning in the Sierra Nevada, California. Res. Note RMRS-RN-41. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Batzer DP, Jackson CR, Mosner M. 2000. Influences of riparian logging on plants and invertebrates in small, depressional wetlands of Georgia, USA. *Hydrobiologia* **441**:123–132.
- Bauer S, Olson J, Cockrill A, van Hattem M, Miller L, Tauzer M, Leppig G. 2015. Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern California watersheds. *PLoS ONE* **10**:e0120016.
- Baxter CV, Fausch KD, Saunders WC. 2005. Tangled webs: reciprocal flows of invertebrate prey link streams and riparian zones. *Freshwater Biology* **50**:201–220.
- Best ML, Welsh HH. 2014. The trophic role of a forest salamander: impacts on invertebrates, leaf litter retention, and the humification process. *Ecosphere* **5**:art16.
- Bingham RE, Papenfuss TJ, Lindstrand III L, Wake DB. 2018. Phylogeography and species boundaries in the *Hydromantes shastae* complex, with description of two new species (Amphibia; Caudata; Plethodontidae). *Bulletin of the Museum of Comparative Zoology* **161**:403–427.
- Blaustein AR, Beatty JJ, Olson DH, Storm RM. 1995. The biology of amphibians and reptiles in old growth forests in the Pacific Northwest. Gen. Tech. Rep. PNW-GTR-337. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

- Blaustein AR, Walls SC, Bancroft BA, Lawler JJ, Searle CL, Gervasi SS. 2010. Direct and indirect effects of climate change on amphibian populations. *Diversity* **2**:281–313.
- Bogaerts S. 2004. Temperature tolerance of captive salamanders during a heat wave. *Podarcis* **5**:15–22.
- Brosfokske KD, Chen J, Naiman RJ, Franklin JF. 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. *Ecological Applications* **7**:1188–1200.
- Burton TM, Likens GE. 1975. Energy flow and nutrient cycling in salamander populations in the Hubbard Brook Experimental Forest, New Hampshire. *Ecology* **56**:1068–1080.
- Bury GW. 2015. An integrated approach to gauge the effects of global climate change on headwater stream ecosystems. Ph.D dissertation. Oregon State University, Corvallis, OR.
- Bury RB. 1972. Small mammals and other prey in the diet of the Pacific giant salamander (*Dicamptodon ensatus*). *American Midland Naturalist* **87**:524–526.
- Bury RB. 2004. Wildfire, fuel reduction, and herpetofaunas across diverse landscape mosaics in northwestern forests. *Conservation Biology* **18**:968–975.
- Bury RB, Corn PS. 1988a. Responses of aquatic and streamside amphibians to timber harvest: a review. Pages 165–181 in K. J. Raedeke, editor. *Streamside management: riparian wildlife and forestry interactions*. University of Washington, College of Forest Resources, Seattle, WA.
- Bury RB, Corn PS. 1988b. Douglas-fir forests in the Oregon and Washington Cascades: relation of the herpetofauna to stand age and moisture. Gen. Tech. Rep. RM-166. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Bury RB, Major DJ, Pilliod D. 2002. Responses of amphibians to fire disturbance in Pacific Northwest forests: a review. Pages 34–42 in W. M. Ford, K. R. Russell, and C. E. Moorman, editors. *The role of fire for nongame wildlife management and community restoration: traditional uses and new directions*. Gen. Tech. Rep. NE-288. U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Newtown Square, PA.
- Bury RB, Pearl CA. 1999. Klamath-Siskiyou herpetofauna: biogeographic patterns and conservation strategies. *Natural Areas Journal* **19**:10.
- Caruso NM, Sears MW, Adams DC, Lips KR. 2014. Widespread rapid reductions in body size of adult salamanders in response to climate change. *Global Change Biology* **20**:1751–1759.
- Case MJ. 2014. Assessing climate change vulnerability of species in northwestern North America. Ph.D dissertation. University of Washington, Seattle, WA.
- CDFW. 2015. California State Wildlife Action Plan, 2015 Update: a conservation legacy for Californians. Prepared with assistance from Ascent Environmental, Inc. California Department of Fish and Wildlife, Sacramento, CA.
- CDFW. 2019. State and federally listed Endangered and Threatened animals in California: April 23, 2019. California Department of Fish and Wildlife, Sacramento, CA. Available from <http://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=109405&inline> (accessed May 8, 2019).
- Cloern JE et al. 2011. Projected evolution of California's San Francisco Bay-Delta-River System in a century of climate change. *PLoS ONE* **6**:e24465.
- Cohen JM, Civitello DJ, Venesky MD, McMahon TA, Rohr JR. 2019. An interaction between climate change and infectious disease drove widespread amphibian declines. *Global Change Biology* **25**:927–937.
- Cook BI, Ault TR, Smerdon JE. 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Science Advances* **1**:e1400082.
- Corn PS, Bury RB, Hyde EJ. 2003. Conservation of North American stream amphibians. Pages 24–36 in R. D. Semlitsch, editor. *Amphibian conservation*. Smithsonian Books, Washington, D.C.
- Cummer MR, Painter CW. 2007. Three case studies of the effect of wildfire on the Jemez Mountains salamander (*Plethodon neomexicanus*): microhabitat temperatures, size distributions, and a historical locality perspective. *The Southwestern Naturalist* **52**:26–37.

- Curtis JM, Taylor EB. 2004. The genetic structure of coastal giant salamanders (*Dicamptodon tenebrosus*) in a managed forest. *Biological Conservation* **115**:45–54.
- Cushman SA. 2006. Effects of habitat loss and fragmentation on amphibians: a review and prospectus. *Biological Conservation* **128**:231–240.
- Davic RD, Welsh HH. 2004. On the ecological roles of salamanders. *Annual Review of Ecology, Evolution, and Systematics* **35**:405–434.
- Deitloff J. 2011. Sympatry between two wide-ranging salamander species. *IRCF Amphibians and Reptiles* **18**:7–11.
- DeMaynadier PG, Hunter ML Jr. 1995. The relationship between forest management and amphibian ecology: a review of the North American literature. *Environmental Reviews* **3**:230–261.
- Dettinger M. 2011. Climate change, atmospheric rivers, and floods in California – a multimodel analysis of storm frequency and magnitude changes. *Journal of the American Water Resources Association* **47**:514–523.
- Diffenbaugh NS, Swain DL, Touma D. 2015. Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences* **112**:3931–3936.
- Diller LV, Wallace RL. 1996. Distribution and habitat of *Rhyacotriton variegatus* in managed, young growth forests in north coastal California. *Journal of Herpetology* **30**:184–191.
- Doerr SH, Shakesby RA, Walsh RPD. 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth-Science Reviews* **51**:33–65.
- Dunham JB, Rosenberger AE, Luce CH, Rieman BE. 2007. Influences of wildfire and channel reorganization on spatial and temporal variation in stream temperature and the distribution of fish and amphibians. *Ecosystems* **10**:335–346.
- Durance I, Ormerod SJ. 2007. Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology* **13**:942–957.
- Dwire KA, Kauffman JB. 2003. Fire and riparian ecosystems in landscapes of the western USA. *Forest Ecology and Management* **178**:61–74.
- Elliott L, Gerhardt C, Davidson C. 2009. *The frogs and toads of North America: a comprehensive guide to their identification, behavior, and calls*. Houghton Mifflin Harcourt, New York, NY.
- Emel SL, Olson DH, Knowles LL, Storfer A. 2019. Comparative landscape genetics of two endemic torrent salamander species, *Rhyacotriton kezeri* and *R. variegatus*: implications for forest management and species conservation. *Conservation Genetics* **20**:801–815.
- Emel SL, Storfer A. 2015. Landscape genetics and genetic structure of the southern torrent salamander, *Rhyacotriton variegatus*. *Conservation Genetics* **16**:209–221.
- Ferguson DE. 1961. The geographic variation of *Ambystoma macrodactylum* Baird, with the description of two new subspecies. *American Midland Naturalist* **65**:311–338.
- Flint LE, Flint AL. 2014. California Basin Characterization Model: a dataset of historical and future hydrologic response to climate change (Ver. 1.1, May 2017). U.S. Geological Survey Data Release. Available from <https://doi.org/10.5066/F76T0JPB>.
- Flint LE, Flint AL, Thorne JH, Boynton R. 2013. Fine-scale hydrologic modeling for regional landscape applications: the California Basin Characterization Model development and performance. *Ecological Processes* **2**:25.
- Frey SJK, Hadley AS, Johnson SL, Schulze M, Jones JA, Betts MG. 2016. Spatial models reveal the microclimatic buffering capacity of old-growth forests. *Science Advances* **2**:e1501392.
- Fuller TE. 2008. The spatial ecology of the exotic bullfrog (*Rana catesbeiana*) and its relationship to the distribution of the native herpetofauna in a managed river system. Master of Science thesis. Humboldt State University, Arcata, CA.

- Funk WC, Dunlap WW. 1999. Colonization of high-elevation lakes by long-toed salamanders (*Ambystoma macrodactylum*) after the extinction of introduced trout populations. *Canadian Journal of Zoology* **77**:1759–1767.
- Gamradt SC, Kats LB. 1996. Effect of introduced crayfish and mosquitofish on California newts. *Conservation Biology* **10**:1155–1162.
- Gershunov A, Guirguis K. 2012. California heat waves in the present and future. *Geophysical Research Letters* **39**:L18710.
- Giordano AR, Ridenhour BJ, Storfer A. 2007. The influence of altitude and topography on genetic structure in the long-toed salamander (*Ambystoma macrodactylum*). *Molecular Ecology* **16**:1625–1637.
- Gomez DM, Anthony RG. 1996. Amphibian and reptile abundance in riparian and upslope areas of five forest types in western Oregon. *Northwest Science* **70**:109–119.
- Good DA, Wake DB. 1992. Geographic variation and speciation in the torrent salamanders of the genus *Rhyacotriton* (Caudata: Rhyacotritonidae). University of California Press, Berkeley, CA.
- Grant EHC. 2018. Characterizing local and range wide variation in demography and adaptive capacity of a forest indicator species. Final report. Northeast Climate Adaptation Science Center, Amherst, MA.
- Grantham TEW, Carlisle DM, McCabe GJ, Howard JK. 2018. Sensitivity of streamflow to climate change in California. *Climatic Change* **149**:427–441.
- Griffin D, Anchukaitis KJ. 2014. How unusual is the 2012–2014 California drought? *Geophysical Research Letters* **41**:9017–9023.
- Hamlet AF, Mote PW, Clark MP, Lettenmaier DP. 2005. Effects of temperature and precipitation variability on snowpack trends in the western United States. *Journal of Climate* **18**:4545–4561.
- Harris RN, Ludwig PM. 2004. Resource level and reproductive frequency in female four-toed salamanders, *Hemidactylium scutatum*. *Ecology* **85**:1585–1590.
- Hendrickson JR. 1954. Ecology and systematics of salamanders of the genus *Batrachoseps*. *Zoology* **54**:1–46.
- Herrington RE. 1988. Talus use by amphibians and reptiles in the Pacific Northwest. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
- Hillyard SD. 1999. Behavioral, molecular and integrative mechanisms of amphibian osmoregulation. *Journal of Experimental Zoology* **283**:662–674.
- Hof C, Araújo MB, Jetz W, Rahbek C. 2011. Additive threats from pathogens, climate and land-use change for global amphibian diversity. *Nature* **480**:516–519.
- Hossack BR, Pilliod DS. 2011. Amphibian responses to wildfire in the western United States: emerging patterns from short-term studies. *Fire Ecology* **7**:129–144.
- Humphries P, Baldwin DS. 2003. Drought and aquatic ecosystems: An introduction. *Freshwater Biology* **48**:1141–1146.
- Huss M, Huntley L, Vredenburg V, Johns J, Green S. 2013. Prevalence of *Batrachochytrium dendrobatidis* in 120 archived specimens of *Lithobates catesbeianus* (American bullfrog) collected in California, 1924–2007. *EcoHealth* **10**:339–343.
- Isaak DJ et al. 2017. The NorWeST summer stream temperature model and scenarios for the western U.S.: a crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. *Water Resources Research* **53**:9181–9205.
- Jaeger RG. 1979. Fluctuations in prey availability and food limitation for a terrestrial salamander. *Oecologia* **44**:335–341.
- Jaeger RG, Wicknick JA, Griffis MR, Anthony CD. 1995. Socioecology of a terrestrial salamander: juveniles enter adult territories during stressful foraging periods. *Ecology* **76**:533–543.

- Johnston B, Frid L. 2002. Clearcut logging restricts the movements of terrestrial Pacific giant salamanders (*Dicamptodon tenebrosus* Good). *Canadian Journal of Zoology* **80**:2170–2177.
- Karraker NE, Gibbs JP. 2011. Road deicing salt irreversibly disrupts osmoregulation of salamander egg clutches. *Environmental Pollution* **159**:833–835.
- Karraker NE, Welsh HH. 2006. Long-term impacts of even-aged timber management on abundance and body condition of terrestrial amphibians in Northwestern California. *Biological Conservation* **131**:132–140.
- Karuk Tribe. 2019. Karuk Climate Adaptation Plan. Karuk Tribe, Orleans, CA. Available from <https://karuktribeclimatechangeprojects.com/climate-adaptation-plan/> (accessed August 22, 2019).
- Keyser A, Westerling AL. 2017. Climate drives inter-annual variability in probability of high severity fire occurrence in the western United States. *Environmental Research Letters* **12**:065003.
- Klein RD, McKee T, Nystrom K. 2017. Shrinking streamflows in the Redwood Region. Pages 187–197 in R. B. Standiford and Y. S. Valachovic, editors. *Coast Redwood Science Symposium—2016: past successes and future direction*. Gen. Tech. Rep. PSW-GTR-258. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.
- Kloeppel BD, Clinton BD, Vose JM, Cooper AR. 2003. Drought impacts on tree growth and mortality of southern Appalachian forests. Pages 43–55 in D. Greenland, D. G. Goodin, and R. C. Smith, editors. *Climate variability and ecosystem response at Long-term Ecological Research Sites*. Oxford University Press, New York, NY.
- Kluber MR, Olson DH, Puettmann KJ. 2008. Amphibian distributions in riparian and upslope areas and their habitat associations on managed forest landscapes of the Oregon Coast Range. *Forest Ecology and Management* **256**:529–535.
- Kluber MR, Olson DH, Puettmann KJ. 2009. Thermal profiles of downed wood under different forest management regimes in the Oregon Coast Range and their potential impact on plethodontid salamander habitat. *Northwest Science* **83**:25–34.
- Lake PS. 2003. Ecological effects of perturbation by drought in flowing waters. *Freshwater Biology* **48**:1161–1172.
- Law BE, Waring RH. 2015. Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests. *Forest Ecology and Management* **355**:4–14.
- Lawler JJ, Shafer SL, Bancroft BA, Blaustein AR. 2010. Projected climate impacts for the amphibians of the Western Hemisphere. *Conservation Biology* **24**:38–50.
- Leng G, Huang M, Voisin N, Zhang X, Asrar GR, Leung LR. 2016. Emergence of new hydrologic regimes of surface water resources in the conterminous United States under future warming. *Environmental Research Letters* **11**:114003.
- Lindenmayer DB, Noss RF. 2006. Salvage logging, ecosystem processes, and biodiversity conservation. *Conservation Biology* **20**:949–958.
- Major DJ. 2005. Effects of fire disturbance on terrestrial salamanders in mixed-coniferous forests of the Klamath/Siskiyou region of the Pacific Northwest. Ph.D dissertation. Utah State University, Logan, UT.
- Mann ML, Batllori E, Moritz MA, Waller EK, Berck P, Flint AL, Flint LE, Dolfi E. 2016. Incorporating anthropogenic influences into fire probability models: effects of human activity and climate change on fire activity in California. *PLoS ONE* **11**:e0153589.
- Mao J, Nierop KGJ, Dekker SC, Dekker LW, Chen B. 2019. Understanding the mechanisms of soil water repellency from nanoscale to ecosystem scale: a review. *Journal of Soils and Sediments* **19**:171–185.
- Marsh DM, Beckman NG. 2004. Effects of forest roads on the abundance and activity of terrestrial salamanders. *Ecological Applications* **14**:1882–1891.

- Martel A, Blooi M, Adriaensen C, Van Rooij P, Beukema W, Fisher MC, Farrer RA, Schmidt BR, Tobler U, Goka K. 2014. Recent introduction of a chytrid fungus endangers Western Palearctic salamanders. *Science* **346**:630–631.
- Martel A, Spitzen-van der Sluijs A, Blooi M, Bert W, Ducatelle R, Fisher MC, Woeltjes A, Bosman W, Chiers K, Bossuyt F. 2013. *Batrachochytrium salamandrivorans* sp. nov. causes lethal chytridiomycosis in amphibians. *Proceedings of the National Academy of Sciences* **110**:15325–15329.
- McComb WC, McGarigal K, Anthony RG. 1993. Small mammal and amphibian abundance in streamside and upslope habitats of mature Douglas-fir stands, western Oregon. *Northwest Science* **67**:7–15.
- McMenamin SK, Hadly EA, Wright CK. 2008. Climatic change and wetland desiccation cause amphibian decline in Yellowstone National Park. *Proceedings of the National Academy of Sciences* **105**:16988–16993.
- Milanovich J, Trauth SE, Saugey DA, Jordan RR. 2006. Fecundity, reproductive ecology, and influence of precipitation on clutch size in the western slimy salamander (*Plethodon albagula*). *Herpetologica* **62**:292–301.
- Milanovich JR, Peterman WE, Nibbelink NP, Maerz JC. 2010. Projected loss of a salamander diversity hotspot as a consequence of projected global change. *PLoS ONE* **5**:e12189.
- Miller JD, Skinner CN, Safford HD, Knapp EE, Ramirez CM. 2012. Trends and causes of severity, size, and number of fires in northwestern California, USA. *Ecological Applications* **22**:184–203.
- Miller MP, Haig SM, Wagner RS. 2006. Phylogeography and spatial genetic structure of the southern torrent salamander: implications for conservation and management. *Journal of Heredity* **97**:561–570.
- Minshall GW, Robinson CT, Lawrence DE. 1997. Postfire responses of lotic ecosystems in Yellowstone National Park, USA. *Canadian Journal of Fisheries and Aquatic Sciences* **54**:2509–2525.
- Nauman RS, Olson DH. 2004. Surveys for terrestrial amphibians in Shasta County, California, with notes on the distribution of Shasta salamanders (*Hydromantes shastae*). *Northwestern Naturalist* **85**:35–38.
- Norgaard KM, Vinyeta K, Hillman L, Tripp B, Lake F. 2016. Karuk Tribe climate vulnerability assessment: assessing vulnerabilities from the increased frequency of high severity fire. Karuk Tribe Department of Natural Resources, Orleans, CA.
- North American Bsal Task Force. 2019. A North American strategic plan to control invasions of the lethal salamander pathogen *Batrachochytrium salamandrivorans*. Available from <http://www.salamanderfungus.org/wp-content/uploads/2019/03/Bsal-Strategic-Plan-Final.pdf> (accessed July 23, 2019).
- Nussbaum RA, Brodie ED, Storm RM. 1983. *Amphibians and reptiles of the Pacific Northwest*. University Press of Idaho, Moscow, ID.
- O’Hanlon SJ et al. 2018. Recent Asian origin of chytrid fungi causing global amphibian declines. *Science* **360**:621–627.
- Olson DH. 2014. Salamanders have spiritual value for the Squamish Nation in British Columbia, Canada. November 2014 Year of the Salamander Newsletter. Partners in Amphibian and Reptile Conservation.
- Olson DH. 2015. The science of 50-foot riparian buffers in headwaters. *Western Forester* **60**:10–11.
- Olson DH, Anderson PD, Frissell CA, Welsh HH, Bradford DF. 2007. Biodiversity management approaches for stream–riparian areas: perspectives for Pacific Northwest headwater forests, microclimates, and amphibians. *Forest Ecology and Management* **246**:81–107.
- Olson DH, Burnett KM. 2009. Design and management of linkage areas across headwater drainages to conserve biodiversity in forest ecosystems. *Forest Ecology and Management* **258**:S117–S126.

- Olson DH, Burnett KM. 2013. Geometry of forest landscape connectivity: pathways for persistence. Pages 220–238 in P. D. Anderson and K. L. Ronnenberg, editors. Density management in the 21st century: west side story. Gen. Tech. Rep. PNW–GTR–880. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- Olson DH, Burton JI. 2014. Near-term effects of repeated thinning with riparian buffers on headwater stream vertebrates and habitats in Oregon, USA. *Forests* **5**:2703–2729.
- Olson DH, Clayton DR, Reilly EC, Nauman RS, Devlin B, Welsh HH. 2009. Conservation of the Siskiyou Mountains Salamander (*Plethodon stormi*). *Northwest Fauna* **6**:1–73.
- Olson DH, Flitcroft RL. 2018. Appendix 1: Aquatic-riparian invasive species of the Northwest Forest Plan area. Pages 582–595 Chapter 7: The Aquatic Conservation Strategy of the Northwest Forest Plan - a review of the relevant science after 23 years. Pages 461–624 in T. A. Spies, P. A. Stine, R. Gravenmier, J. W. Long, and M. J. Reilly, editors. Synthesis of science to inform land management within the Northwest Forest Plan area. Gen. Tech. Rep. PNW-GTR-966. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- Olson DH, Kluber MR. 2014. Plethodontid salamander distributions in managed forest headwaters in western Oregon. *Herpetological Conservation and Biology* **9**:76–96.
- Olson DH, Leirness JB, Cunningham PG, Steel EA. 2014. Riparian buffers and forest thinning: effects on headwater vertebrates 10 years after thinning. *Forest Ecology and Management* **321**:81–93.
- Olson DH, Rugger C. 2007. Preliminary study of the effects of headwater riparian reserves with upslope thinning on stream habitats and amphibians in western Oregon. *Forest Science* **53**:331–342.
- Olson DH, Weaver G. 2007. Vertebrate assemblages associated with headwater hydrology in western Oregon managed forests. *Forest Science* **53**:343–355.
- Palik B, Batzer DP, Buech R, Nichols D, Cease K, Egeland L, Streblov DE. 2001. Seasonal pond characteristics across a chronosequence of adjacent forest ages in northern Minnesota, USA. *Wetlands* **21**:532–542.
- Palis JG. 1996. Flatwoods salamander (*Ambystoma cingulatum* Cope). *Natural Areas Journal* **16**:49–54.
- Parks SA, Miller C, Abatzoglou JT, Holsinger LM, Parisien M-A, Dobrowski SZ. 2016. How will climate change affect wildland fire severity in the western US? *Environmental Research Letters* **11**:035002.
- Parks SA, Miller C, Parisien M-A, Holsinger LM, Dobrowski SZ, Abatzoglou J. 2015. Wildland fire deficit and surplus in the western United States, 1984–2012. *Ecosphere* **6**:1–13.
- Perry DA, Hessburg PF, Skinner CN, Spies TA, Stephens SL, Taylor AH, Franklin JF, McComb B, Riegel G. 2011. The ecology of mixed severity fire regimes in Washington, Oregon, and Northern California. *Forest Ecology and Management* **262**:703–717.
- Petranka JW. 1998. Salamanders of the United States and Canada. Smithsonian Institution Press, Washington, D.C.
- Petranka JW, Sih A. 1986. Environmental instability, competition, and density-dependent growth and survivorship of a stream-dwelling salamander. *Ecology* **67**:729–736.
- Pettit NE, Naiman RJ. 2007. Fire in the riparian zone: characteristics and ecological consequences. *Ecosystems* **10**:673–687.
- Pierce DW, Kalansky JF, Cayan DR. 2018. Climate, drought, and sea level rise scenarios for the Fourth California Climate Assessment. California’s Fourth Climate Change Assessment. Publication Number: CNRA-CEC-2018-006. California Energy Commission, Sacramento, CA.
- Pilliod DS, Bury RB, Hyde EJ, Pearl CA, Corn PS. 2003. Fire and amphibians in North America. *Forest Ecology and Management* **178**:163–181.
- Pilliod DS, Fronzuto JA. 2005. *Ambystoma macrodactylum*, Long-toed salamander. Pages 617–621 in M. J. Lannoo, editor. Amphibian declines: the conservation status of United States species. University of California Press, Berkeley, CA.

- Piotrowski JS, Annis SL, Longcore JE. 2004. Physiology of *Batrachochytrium dendrobatidis*, a chytrid pathogen of amphibians. *Mycologia* **96**:9–15.
- Pough FH. 1980. The advantages of ectothermy for tetrapods. *The American Naturalist* **115**:92–112.
- Pounds JA, Bustamante MR, Coloma LA, Consuegra JA, Fogden MP, Foster PN, La Marca E, Masters KL, Merino-Viteri A, Puschendorf R. 2006. Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature* **439**:161.
- Price SJ, Browne RA, Dorcas ME. 2012. Resistance and resilience of a stream salamander to suprasedasonal drought. *Herpetologica* **68**:312–323.
- Rapacciuolo G et al. 2014. Beyond a warming fingerprint: individualistic biogeographic responses to heterogeneous climate change in California. *Global Change Biology* **20**:2841–2855.
- Rauscher SA, Pal JS, Diffenbaugh NS, Benedetti MM. 2008. Future changes in snowmelt-driven runoff timing over the western US. *Geophysical Research Letters* **35**:L16703.
- Reeder NMM, Pessier AP, Vredenburg VT. 2012. A reservoir species for the emerging amphibian pathogen *Batrachochytrium dendrobatidis* thrives in a landscape decimated by disease. *PLOS ONE* **7**:e33567.
- Reeves GH, Olson DH, Wondzell SM, Bisson PA, Gordon S, Miller SA, Long JW, Furniss MJ. 2018. Chapter 7: The Aquatic Conservation Strategy of the Northwest Forest Plan - a review of the relevant science after 23 years. Pages 461–624 in T. A. Spies, P. A. Stine, R. Gravenmier, J. W. Long, and M. J. Reilly, editors. Synthesis of science to inform land management within the Northwest Forest Plan area. Gen. Tech. Rep. PNW-GTR-966. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- Reilly E, Clayton D, Nauman RS, Olson DH, Welsh HH, Devlin B. 2009. Chapter 2: Spatial model of optimal habitat for the Siskiyou Mountains salamander north of the Siskiyou crest. Pages 23–25 in D. H. Olson, D. Clayton, R. S. Nauman, and H. H. Welsh, editors. Conservation of the Siskiyou Mountains Salamander (*Plethodon stormi*). Northwest Fauna 6:1-73.
- Reilly SB, Marks SB, Jennings WB. 2012. Defining evolutionary boundaries across parapatric ecomorphs of black salamanders (*Aneides flavipunctatus*) with conservation implications. *Molecular Ecology* **21**:5745–5761.
- Reilly SB, Mulks MF, Reilly JM, Jennings WB, Wake DB. 2013. Genetic diversity of black salamanders (*Aneides flavipunctatus*) across watersheds in the Klamath Mountains. *Diversity* **5**:657–679.
- Reilly SB, Wake DB. 2015. Cryptic diversity and biogeographical patterns within the black salamander (*Aneides flavipunctatus*) complex. *Journal of Biogeography* **42**:280–291.
- Richgels KL, Russell RE, Adams MJ. 2016. Spatial variation in risk and consequence of *Batrachochytrium salamandrivorans* introduction in the USA. *Royal Society Open Science* **3**.
- Rohr JR, Palmer BD. 2005. Aquatic herbicide exposure increases salamander desiccation risk eight months later in a terrestrial environment. *Environmental Toxicology and Chemistry* **24**:1253–1258.
- Rollins-Smith LA. 2017. Amphibian immunity–stress, disease, and climate change. *Developmental & Comparative Immunology* **66**:111–119.
- Rome LC, Stevens ED, John-Alder HB. 1992. The influence of temperature and thermal acclimation on physiological function. Pages 205–205 in M. E. Feder and W. W. Burggren, editors. Environmental physiology of the amphibians. University of Chicago Press, Chicago, IL.
- Rundio DE, Olson DH. 2007. Influence of headwater site conditions and riparian buffers on terrestrial salamander response to forest thinning. *Forest Science* **53**:320–330.
- Ryan ME, Johnson JR, Fitzpatrick BM, Lowenstine LJ, Picco AM, Shaffer HB. 2013. Lethal effects of water quality on threatened California salamanders but not on co-occurring hybrid salamanders. *Conservation Biology* **27**:95–102.

- Ryan ME, Palen WJ, Adams MJ, Rochefort RM. 2014. Amphibians in the climate vise: loss and restoration of resilience of montane wetland ecosystems in the western US. *Frontiers in Ecology and the Environment* **12**:232–240.
- Rykken JJ, Chan SS, Moldenke AR. 2007. Headwater riparian microclimate patterns under alternative forest management treatments. *Forest Science* **53**:270–280.
- Safford HD, Van de Water KM. 2014. Using fire return interval departure (FRID) analysis to map spatial and temporal changes in fire frequency on national forest lands in California. Res. Pap. PSW-RP-266. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.
- Sagar JP, Olson DH, Schmitz RA. 2007. Survival and growth of larval coastal giant salamanders (*Dicamptodon tenebrosus*) in streams in the Oregon Coast Range. *Copeia* **2007**:123–130.
- Savage WK, Fremier AK, Shaffer HB. 2010. Landscape genetics of alpine Sierra Nevada salamanders reveal extreme population subdivision in space and time. *Molecular Ecology* **19**:3301–3314.
- Sawaske SR, Freyberg DL. 2014. An analysis of trends in baseflow recession and low-flows in rain-dominated coastal streams of the Pacific coast. *Journal of Hydrology* **519**:599–610.
- Scott DE. 1994. The effect of larval density on adult demographic traits in *Ambystoma opacum*. *Ecology* **75**:1383–1396.
- Scott DE, Fore MR. 1995. The effect of food limitation on lipid levels, growth, and reproduction in the marbled salamander, *Ambystoma opacum*. *Herpetologica* **51**:462–471.
- Searcy CA, Gray LN, Trenham PC, Shaffer HB. 2014. Delayed life history effects, multilevel selection, and evolutionary trade-offs in the California tiger salamander. *Ecology* **95**:68–77.
- Semlitsch RD, Bodie JR. 2003. Biological criteria for buffer zones around wetlands and riparian habitats for amphibians and reptiles. *Conservation Biology* **17**:1219–1228.
- Semlitsch RD, O'Donnell KM, Thompson III FR. 2014. Abundance, biomass production, nutrient content, and the possible role of terrestrial salamanders in Missouri Ozark forest ecosystems. *Canadian Journal of Zoology* **92**:997–1004.
- Semlitsch RD, Todd BD, Blomquist SM, Calhoun AJ, Gibbons JW, Gibbs JP, Graeter GJ, Harper EB, Hocking DJ, Hunter ML Jr. 2009. Effects of timber harvest on amphibian populations: understanding mechanisms from forest experiments. *BioScience* **59**:853–862.
- Sette CM, Vredenburg VT, Zink AG. 2015. Reconstructing historical and contemporary disease dynamics: a case study using the California slender salamander. *Biological Conservation* **192**:20–29.
- Shoo LP et al. 2011. Engineering a future for amphibians under climate change. *Journal of Applied Ecology* **48**:487–492.
- Spotila JR. 1972. Role of temperature and water in the ecology of lungless salamanders. *Ecological Monographs* **42**:95–125.
- Sredl MS, Wallace JE. 2000. Management of the amphibians of Fort Huachuca, Cochise County, Arizona. Nongame and Endangered Wildlife Program Technical Report 166. Arizona Game and Fish Department, Phoenix, AZ.
- Stephens SL, Martin RE, Clinton NE. 2007. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. *Forest Ecology and Management* **251**:205–216.
- Stewart IT, Cayan DR, Dettinger MD. 2004. Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario. *Climatic Change* **62**:217–232.
- Stewart IT, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western North America. *Journal of Climate* **18**:1136–1155.
- Stuart SN, Chanson JS, Cox NA, Young BE, Rodrigues AS, Fischman DL, Waller RW. 2004. Status and trends of amphibian declines and extinctions worldwide. *Science* **306**:1783–1786.
- Swain DL, Langenbrunner B, Neelin JD, Hall A. 2018. Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change* **8**:427.

- Syphard AD, Keeley JE, Pfaff AH, Ferschweiler K. 2017. Human presence diminishes the importance of climate in driving fire activity across the United States. *Proceedings of the National Academy of Sciences* **114**:13750–13755.
- Tague C, Seaby L, Hope A. 2009. Modeling the eco-hydrologic response of a Mediterranean type ecosystem to the combined impacts of projected climate change and altered fire frequencies. *Climatic Change* **93**:137–155.
- Taylor AH, Trouet V, Skinner CN, Stephens S. 2016. Socioecological transitions trigger fire regime shifts and modulate fire–climate interactions in the Sierra Nevada, USA, 1600–2015 CE. *Proceedings of the National Academy of Sciences* **113**:13684–13689.
- Thompson C, Sweitzer R, Gabriel M, Purcell K, Barrett R, Poppenga R. 2014. Impacts of rodenticide and insecticide toxicants from marijuana cultivation sites on fisher survival rates in the Sierra National Forest, California. *Conservation Letters* **7**:91–102.
- Thomson RC, Wright AN, Shaffer HB. 2016. California amphibian and reptile species of special concern. University of California Press, Oakland, CA.
- Tyler T, Liss WJ, Ganio L, Larson GL, Hoffman RL, Deimling E, Lomnický GA. 1998. Interactions between introduced trout and larval salamanders (*Ambystoma macrodactylum*) in high-elevation lakes. *Conservation Biology* **12**:94–105.
- Van Rooij P, Martel A, Haesebrouck F, Pasmans F. 2015. Amphibian chytridiomycosis: a review with focus on fungus-host interactions. *Veterinary Research* **46**:137.
- Vredenburg VT, Felt SA, Morgan EC, McNally SVG, Wilson S, Green SL. 2013. Prevalence of *Batrachochytrium dendrobatidis* in *Xenopus* collected in Africa (1871–2000) and in California (2001–2010). *PLoS ONE* **8**:e63791.
- Wahl ER, Zorita E, Trouet V, Taylor AH. 2019. Jet stream dynamics, hydroclimate, and fire in California from 1600 CE to present. *Proceedings of the National Academy of Sciences* **116**:5393–5398.
- Wake DB, Vredenburg VT. 2008. Are we in the midst of the sixth mass extinction? A view from the world of amphibians. *Proceedings of the National Academy of Sciences* **105**:11466–11473.
- Walls SC, Barichivich WJ, Brown ME, Scott DE, Hossack BR. 2013. Influence of drought on salamander occupancy of isolated wetlands on the southeastern coastal plain of the United States. *Wetlands* **33**:345–354.
- Walton BM. 2005. Salamanders in forest-floor food webs: environmental heterogeneity affects the strength of top-down effects. *Pedobiologia* **49**:381–393.
- Weinstein SB. 2009. An aquatic disease on a terrestrial salamander: individual and population level effects of the amphibian chytrid fungus, *Batrachochytrium dendrobatidis*, on *Batrachoseps attenuatus* (Plethodontidae). *Copeia* **2009**:653–660.
- Welsh HH. 1990. Relictual amphibians and old-growth forests. *Conservation Biology* **4**:309–319.
- Welsh HH, Droege S. 2001. A case for using plethodontid salamanders for monitoring biodiversity and ecosystem integrity of North American forests. *Conservation Biology* **15**:558–569.
- Welsh HH, Hodgson GR. 2008. Amphibians as metrics of critical biological thresholds in forested headwater streams of the Pacific Northwest, USA. *Freshwater Biology* **53**:1470–1488.
- Welsh HH, Hodgson GR. 2011. Spatial relationships in a dendritic network: the herpetofaunal metacommunity of the Mattole River catchment of northwest California. *Ecography* **34**:49–66.
- Welsh HH, Lind AJ. 1991. The structure of the herpetofaunal assemblage in the Douglas-fir/hardwood forests of northwestern California and southwestern Oregon. Pages 395–413 in L. F. Ruggiero, K. B. Aubry, A. B. Carey, and M. H. Huff, editors. *Wildlife and vegetation of unmanaged Douglas-fir forests*. Gen. Tech. Rep. PNW-GTR-285. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

- Welsh HH, Lind AJ. 1992. Population ecology of two relictual salamanders from the Klamath Mountains of northwestern California. Pages 419–437 in D. R. McCullough and R. H. Barrett, editors. *Wildlife 2001: Populations*. Springer, Dordrecht, Netherlands.
- Welsh HH, Lind AJ. 1996. Habitat correlates of the southern torrent salamander, *Rhyacotriton variegatus* (Caudata: Rhyacotritonidae), in northwestern California. *Journal of Herpetology* **30**:385–398.
- Welsh HH, Pope KL, Boiano D. 2006. Sub-alpine amphibian distributions related to species palatability to non-native salmonids in the Klamath mountains of northern California. *Diversity and Distributions* **12**:298–309.
- Westerling AL. 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**:20150178.
- Westerling AL. 2018. Wildfire simulations for California’s Fourth Climate Change Assessment: projecting changes in extreme wildfire events with a warming climate. California’s Fourth Climate Change Assessment. Publication Number: CCCA4-CEC-2018-014. California Energy Commission, Sacramento, CA.
- Westerling AL, Bryant BP, Preisler HK, Holmes TP, Hidalgo HG, Das T, Shrestha SR. 2011. Climate change and growth scenarios for California wildfire. *Climatic Change* **109**:445–463.
- Xie GY, Olson DH, Blaustein AR. 2016. Projecting the global distribution of the emerging amphibian fungal pathogen, *Batrachochytrium dendrobatidis*, based on IPCC climate futures. *PLoS ONE* **11**:e0160746.
- Yap TA, Koo MS, Ambrose RF, Wake DB, Vredenburg VT. 2015. Averting a North American biodiversity crisis. *Science* **349**:481–482.
- Young MK. 1994. Movement and characteristics of stream-borne coarse woody debris in adjacent burned and undisturbed watersheds in Wyoming. *Canadian Journal of Forest Research* **24**:1933–1938.
- Yuan Z, Martel A, Wu J, Praet SV, Canessa S, Pasmans F. 2018. Widespread occurrence of an emerging fungal pathogen in heavily traded Chinese urodelan species. *Conservation Letters* **11**:e12436.

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

Literature Cited

- EcoAdapt. 2014a. A climate change vulnerability assessment for aquatic resources in the Tongass National Forest. EcoAdapt, Bainbridge Island, WA. 124 pp.
- EcoAdapt. 2014b. A climate change vulnerability assessment for resources of Nez Perce-Clearwater National Forests. Version 3.0. EcoAdapt, Bainbridge Island, WA. 398 pp.
- Glick P, Stein BA, Edelson NA. 2011. Scanning the conservation horizon: A guide to climate change vulnerability assessment. National Wildlife Federation, Washington, D.C.
- Gregg RM, editor. 2018. Hawaiian Islands climate vulnerability and adaptation synthesis. EcoAdapt, Bainbridge Island, WA. 284 pp.

- Hutto SV, Higgason KD, Kershner JM, Reynier WA, Gregg DS. 2015. Climate change vulnerability assessment for the north-central California coast and ocean. Marine Sanctuaries Conservation Series ONMS-15-02. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 473 pp.
- Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Pages 617–652 in M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, editors. Cambridge University Press, Cambridge, UK.
- Kershner JM, editor. 2014. A climate change vulnerability assessment for focal resources of the Sierra Nevada. Version 1.0. EcoAdapt, Bainbridge Island, WA. 418 pp.
- Lawler J. 2010. Pacific Northwest Climate Change Vulnerability Assessment. From <http://climatechangesensitivity.org>
- Manomet Center for Conservation Sciences and National Wildlife Federation. 2012. The vulnerabilities of fish and wildlife habitats in the Northeast to climate change. A report to the Northeastern Association of Fish and Wildlife Agencies and the North Atlantic Landscape Conservation Cooperative. Manomet Center for Conservation Sciences, Plymouth, MA.
- Moss R, Schneider S. 2000. Towards consistent assessment and reporting of uncertainties in the IPCC TAR. In R. Pachauri and T. Taniguchi, editors. *Cross-Cutting Issues in the IPCC Third Assessment Report*. Global Industrial and Social Progress Research Institute (for IPCC), Tokyo.