Native Freshwater Mussels

Northern California Climate Change Vulnerability Assessment Synthesis

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

Peer reviewers for this document included Anonymous (Washington Department of Fish and Wildlife), Emilie Blevins (Xerces Society for Invertebrate Conservation), and Alexa Maine (Confederated Tribes of the Umatilla Indian Reservation). Vulnerability scores were provided by Keith Bensen (National Park Service). Upper Lake workshop participants provided additional comments on the climate change vulnerability of this species group.

Table of Contents

Species Group Description

Freshwater mussels are bivalve mollusks that occupy a variety of freshwater habitats in northern California, including streams, rivers, and lakes (Howard & Cuffey 2003; Furnish 2007; Davis et al. 2013). Freshwater mussels are primarily sedentary filter/siphon feeders, consuming phytoplankton, bacteria, and algae suspended in the water column (Nichols & Garling 2000;

Christian et al. 2004; Nichols et al. 2005; Vaughn et al. 2008). As they feed, freshwater mussels improve water quality through filtration and increase benthic species richness by cycling nutrients into the substrate (Howard & Cuffey 2006; Vaughn et al. 2008). In order to complete metamorphosis and disperse to new habitat, mussel larvae must attach themselves to a host fish, with host fish species varying by mussel species and habitat type (Brim Box et al. 2006; Haag 2012; O'Brien et al. 2013; Maine et al. 2016).

This assessment considers the four native species that are currently distributed within northern California: the western pearlshell mussel *(Margaritifera falcata*), western ridged mussel *(Gonidea angulata*), winged floater (*Anodonta nuttalliana*), and California floater (*Anodonta californiensis*).[1] These four species represent three of the four mussel genera found in western North America (Davis et al. 2013). Within their northern California distribution, the western pearlshell mussel is the most widespread of the three species (Blevins et al. 2017a; Xerces/CTUIR 2019). Winged/California floaters are less widely distributed, and western ridged mussel are a close third (Blevins et al. 2017a; Xerces/CTUIR 2019).

Native Freshwater Mussel Species	Key Life History Characteristics Summary
Western pearlshell mussel (*Margaritifera falcata*)	• Lives 40–60 years, occasionally reaching up to 100 years where habitat/water quality parameters are not driving average lifespan down • Inhabits perennial rivers and streams with cold, clear, highly oxygenated, and slightly acidic water from sea level up to nearly 2,440 m (8,000 ft) in elevation • Often found in boulder-strewn streams with substrates of cobble, gravel, sand, and silt • Dependent on salmonids as host fish, including cutthroat trout (*Oncorhynchus clarkii*), rainbow/steelhead trout (*O. mykiss*), Chinook salmon (*O. tshawytscha*), coho (*O. kisutch*), and brown trout (*Salmo trutta*; non-native)
Western ridged mussel (*Gonidea angulata*)	• Lives 40–60 years • Inhabits lowland and valley lakes, rivers, and creeks at elevations up to nearly 2,130 m (7,000 ft) • Tolerant of a relatively wide range of substrates • Dependent on inland fish species as hosts, including pit sculpin (*Cottus pitensis*), hardhead (*Mylopharodon conocephalus*), tule perch (*Hysterocarpus traski*)

---

[1] The most current naming publication for mollusks, which is considered the taxonomic authority, lists *Anodonta nuttalliana* and *Anodonta californiensis* as separate species (Williams et al. 2017). Although genetic evidence suggests that these likely belong to a single clade or species (Mock et al. 2010), this assessment will follow the current naming conventions outlined in Williams et al. (2017). When referring to scientific publications that synonymize the two species, we will refer to them as California/winged floaters.

Native Freshwater Mussel Species	**Key Life History Characteristics Summary**
Winged/California floater (*Anodonta nuttalliana*)	• Lives 15–30 years • Inhabits lakes, reservoirs, and slow-moving streams as well as low-gradient rivers, typically at lower elevations • Typically found in mud, sand, or gravel substrates • Dependent on inland fish species as hosts, including pit sculpin, torrent sculpin (*C. rhotheus*), Sacramento pikeminnow (*Ptychocheilus grandis*), tule perch, three-spined stickleback (*Gasterosteus aculeatus*), redside shiner (*Richardsonius balteatus*), speckled dace (*Rhinichthys osculus*), hardhead, green sunfish (*Lepomis cyanellus*; non-native)
Source(s): Murphy 1942; Karna & Millemann 1978; Brim Box et al. 2006; Haley et al. 2007; Haag 2012; O'Brien et al. 2013; Maine et al. 2016; Blevins et al. 2017b; Xerces/CTUIR 2019	

Executive Summary

The relative vulnerability of native mussels 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.

Native Mussels	**Rank**	**Confidence**
Sensitivity	Moderate-High	High
Future Exposure	Moderate-High	Moderate
Adaptive Capacity	Low-Moderate	Moderate
Vulnerability	**Moderate-High**	**Moderate**

Sensitivity & Exposure Summary	*Climate and climate-driven factors*: • Streamflow, water temperature, precipitation amount, drought *Disturbance regimes*: • Flooding *Non-climate stressors*: • Dams and water diversions, pollution, other stream sediment sources

Because they require abundant cool, clean water, native freshwater mussels are sensitive to climatic changes that reduce water availability (e.g., altered streamflow, reduced precipitation, increased drought) and decrease water quality (e.g., increased water temperature and sedimentation). Limited water availability can degrade or eliminate freshwater mussel habitat and impact host fish abundance and reproductive success, while warmer water temperatures can lessen fitness and survival of mussels by increasing thermal stress and reducing dissolved oxygen, particularly for mussels in smaller, high-gradient streams. Freshwater mussels reliant on salmonid host fish to reproduce are also affected by climate-driven changes in estuarine and marine environments that lower host fish abundance and potentially lead to phenological mismatches between timing of fish migration and mussel reproduction. Increased flooding can scour habitat and displace adult and juvenile mussels, while dams and water diversions can dewater streams and raise water temperatures, inhibiting mussel growth and reproduction and increasing mortality. Lake-dwelling mussels are similarly subject to lowered lake levels from drought, increasing water temperature, and changes in inland host fish phenology. Additionally, all native freshwater mussels are sensitive to nutrient and heavy metal pollution and the multiple land uses that increase sedimentation in rivers, streams, and lakes.

Adaptive Capacity Summary	*<u>Factors that enhance adaptive capacity</u>* + Relatively long-lived + Potential reproductive flexibility (e.g., hermaphroditism, extended breeding season, or generalist host use) in some species + Host fish association allows potential colonization of new and/or formerly inhabited areas + Ability to improve water quality, creating beneficial conditions for host fish species + Highly valued by northern California tribes *<u>Factors that undermine adaptive capacity</u>*: – Severe population reductions from historical levels – Dependent on host fish species that are vulnerable to climate change impacts – Low genetic diversity likely in some populations – Limited movement in response to environmental changes and limited tolerance of altered habitat – Lack of public understanding of threats and limited policy-based protections

Native freshwater mussel populations have declined precipitously throughout the western United States, with northern California remaining a population refugia for species that formerly had a more extensive distribution in the state. Fragmented habitat and small population sizes limit the potential for genetic adaptation, while dispersal opportunities are limited by the sessile nature of this species group, as well as their reliance on host fish that are also threatened by multiple climate and non-climate stressors (especially salmonids). Although genetic diversity is low as a result of recent population reductions, reproductive plasticity (i.e., hermaphroditism) in some mussel species has the potential to aid in dispersal and population recovery. However, this species group is slow to recover from disturbances and has a limited tolerance of altered habitat as well as a limited ability to move in response to environmental changes. Societal support for freshwater mussel conservation is driven by their high value to northern California tribes as well as the ecosystem services they provide (e.g., improving water quality and benthic diversity). However, the public is generally unaware of the degree to which this species group is imperiled, and policy-based protections for this species group are limited. Managing for mussel population recovery will likely be supported by additional research on mussel life history and distribution to help target actions for habitat restoration and protection. Management actions can also be combined with anadromous fish recovery strategies for mutual benefit.

Sensitivity and Exposure

Native freshwater mussels were evaluated by regional experts as having moderate-high overall sensitivity (high 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.

Potential Changes in Species Group Distribution
• Population declines expected based on vulnerability of aquatic habitat to degradation and loss as a result of climate changes • Future distribution is likely to be impacted by habitat availability and shifts in the abundance and distribution of host fish
Source(s): Pandolfo et al. 2012; Schwalb et al. 2012; Vuln. Assessment Reviewer, pers. comm., 2019

Projections of future freshwater mussel distributions in the western U.S. are not currently available, and the potential for range shifts is likely low. In general, climate models project changes in water quality and seasonal water availability (Isaak et al. 2017; Micheli et al. 2018; Swain et al. 2018; Grantham et al. 2018), as well as the potential for shifts in host fish abundance and distribution (Isaak et al. 2012; Moyle et al. 2013; Katz et al. 2013). Shifts in mussel distribution depend on the availability of suitable habitat either at higher elevations and/or latitudes (Vuln. Assessment Reviewer, pers. comm., 2019), as well as connectivity between river branches that allow host fish dispersal (Inoue & Berg 2017). Declining host fish abundance in mussel habitat is also expected to have a major influence on freshwater mussel distributional patterns (Pandolfo et al. 2012; Schwalb et al. 2013). The potential for range shifts varies depending on species characteristics; for instance, although western ridged mussels rely on host fish that are widely distributed, the distribution of this species remains generally limited to valley bottom or lowland rivers, streams, and lakes. As a result, the species' adaptive capacity for an elevational range shift may also be limited and does not appear to be dictated by the distribution of its host fish (Vuln. Assessment Reviewer, pers. comm., 2019).

A recent spatial analysis comparing the overlap between current western North American mussel distribution with stream temperature projections and other threats (e.g., barriers to host fish passage, surface water diversions, known sources of pollution) identified watersheds that may serve as climate refugia for mussels (Blevins 2018). The lower Klamath basin in northern California appears to have higher potential to provide climate refugia for western ridged mussels and/or diverse mussel assemblages compared to most other areas in the Pacific Northwest and Intermountain West (Blevins 2018). Headwater streams, in particular, may continue to provide refugia for cold-adapted aquatic species (Isaak et al. 2016).

Sensitivity and future exposure to climate and climate-driven factors

Regional experts evaluated native mussels as having moderate-high sensitivity to climate and climate-driven factors (high confidence in evaluation), with an overall moderate-high future exposure to these factors within the study region (low confidence). Key climatic factors that affect native mussels include streamflow, drought, water temperature, and precipitation amount.[2]

Streamflow

Freshwater mussels are adapted to habitats with seasonal hydrologic fluctuations (Howard & Cuffey 2003; Haag 2012). However, mussel abundance is negatively correlated with hydrological variability (i.e., magnitude and frequency of high flows and extreme variation in daily mean flow), likely because these conditions increase riverbed scouring and shear stress that may limit mussel recruitment (Davis et al. 2013). For instance, juvenile mussels are particularly vulnerable to displacement from habitat during high flows (Irmscher & Vaughn 2018). Although the exact mechanism is unknown, mussel growth is also strongly influenced by patterns of streamflow, with high flows corresponding to more limited growth (Black et al. 2010, 2015). Because the majority of annual precipitation occurs during the winter in northern California (Dettinger et al. 2011), growth declines primarily occur during the winter and spring depending on whether rivers are rain- or snow- dominated (Black et al. 2015). This suggests that higher winter peak flows and greater overall variability would likely limit mussel growth (Black et al. 2015), and could also cause mortality by washing mussels away (Hastie et al. 2003).

Large variability in streamflow also reduces the proportion of the channel that is suitable for mussels (Davis et al. 2013). Edge habitats that act as refugia during high peak flows are typically dry during low flow periods, while habitats that remain suitable during low flow periods (e.g., the central channel) are likely to experience fast-moving water and bedload transport (i.e., movement of rocks, cobble, and sediment) during peak flows (Vannote & Minshall 1982; Davis et al. 2013). Sensitivity to flow variability may be further limited by the ability of mussel species to move within the stream channel as conditions change. Western ridged mussels are the most sessile of the western species, increasing their vulnerability to rapid hydrological shifts. Species that prefer habitats with coarse substrate may also have a limited ability to escape from drying channels (Vuln. Assessment Reviewer, pers. comm., 2019). For instance, western pearlshell mussels are often found in large cobble or boulder habitat, tucked between rocks that protect them from high flows and scour events (Howard & Cuffey 2003; Wagschal & Blevins 2017) but make it difficult to move out of drying habitat. Similarly, feeding differences among species could impact their tolerance for changes in flow magnitude and variability; however, this has not been well-studied in western mussels (Vuln. Assessment Reviewer, pers. comm., 2019).

Low flows, such as occurs during periods of severe drought, may cause increased water temperatures and habitat loss due to drying (see below for discussion of water temperature; (Hastie et al. 2003; Haag & Warren 2008; Galbraith et al. 2010). Impacts may be particularly severe in small tributary streams that shift from perennial to intermittent flows, resulting in disconnected pools (Haag & Warren 2008; Galbraith et al. 2010). In addition, low water levels can expose mussels to the air and/or lead to the accumulation of silt, algae, and organic debris on the streambed that hinders growth of juvenile mussels (Hastie et al. 2003). Mussel

---

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

recruitment and dispersal would also be reduced if changes in streamflow alter host fish presence or activity, including the migration of anadromous fish to natal streams (Vuln. Assessment Reviewer, pers. comm., 2019).

<table>
<tr><th colspan="2">Regional Streamflow Trends[3]</th></tr>
<tr><td><i>Historical & current trends:</i>
• 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)</td><td><i>Projected future trends:</i>
• 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)</td></tr>
<tr><th colspan="2">Summary of Potential Impacts on Species Group <i>(see text for citations)</i></th></tr>
<tr><td colspan="2">• Reduced growth and recruitment and increased mortality due to scouring and high flows
• Impaired functioning from increased water temperature and decreased habitat extent during low flows
• Increased mortality due to exposure to air during low flows
• Decreased juvenile recruitment from accumulation of silt, sediment, and organic debris in substrate during low flows
• Reduced recruitment and dispersal if flow variability changes host fish presence or activity</td></tr>
</table>

Water temperature

Higher water temperatures could reduce growth, recruitment, and survival for freshwater mussels (Spooner & Vaughn 2008; Galbraith et al. 2010; Pandolfo et al. 2010; Allard et al. 2015). Thermal stress significantly reduces burrowing behavior in mussels, potentially increasing their vulnerability to emersion (i.e., exposure to air), high flows, and predators (Archambault et al. 2013). Warmer temperatures and associated declines in dissolved oxygen levels also impact physiological processes, although species that normally live in habitats with lower oxygen levels (e.g., lakes) may be better able to regulate their oxygen consumption (Chen et al. 2001; Hastie et al. 2003). Mussels may be able to acclimatize somewhat to more gradual warming, but are likely to be negatively affected by extreme thermal events resulting from heat waves, drought,

---

[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.

and/or water withdrawals, especially in smaller streams that heat up more rapidly (Hastie et al. 2003). Over longer time scales, studies in the southern U.S. documented shifts in community composition towards thermally-tolerant species (Spooner & Vaughn 2008) and decreases in water filtration and other ecosystem services that mussels provide (Vaughn et al. 2015).

Increased water temperature can also alter mussel reproductive phenology. The precise timing of glochidial release likely depends on water temperature for some species (O'Brien et al. 2013; Allard et al. 2015), and can occur earlier in warmer water for western pearlshell mussels (Meyers & Millemann 1977). However, potential changes in the timing of spawning due to warmer water temperatures may be tempered by mussel-host fish interactions (Hastie et al. 2003). While warmer water temperatures could extend spawning time earlier in the season, higher water temperatures may also affect migration and spawning behavior of host fish in ways that uncouple host fish presence and mussel reproduction timing (Hastie et al. 2003; Terui et al. 2014). In addition, freshwater mussels are generally more tolerant of warmer temperatures than their host fishes, effectively rendering them more vulnerable to a warming aquatic environment than they would be without this dependency (Pandolfo et al. 2012).

Warmer water temperatures, combined with reduced water levels, may shift phytoplankton community dynamics and disrupt feeding of zooplankton, a freshwater mussel food item (Vincent 2009). Warmer water temperatures are also likely to lower dissolved oxygen levels in freshwater mussel habitat (Voshell 2002; Fang & Stefan 2009; Vincent 2009).

Regional Water Temperature Trends	
Historical & current trends: • ~0.1°C (0.2°F) per decade increase in mean August stream temperatures in northwestern California from 1976–2015 (Isaak et al. 2017) ○ Corresponds to a 0.4°C (0.7°F) increase in air temperature and 5.3% decrease in discharge per decade	*Projected future trends:* • 0.4–0.8°C (0.7–1.4°F) per decade increase in mean August stream temperatures in northwestern California by the 2080s (Isaak et al. 2017) ○ Corresponds to a 3.6°C (6.5°F) increase in air temperature and 1.2% decrease in stream discharge • 1–3°C (1.8–5.4°F) increase in the temperature of the Sacramento River by 2100 (Cloern et al. 2011)
Summary of Potential Impacts on Species Group *(see text for citations)*	
• Increased energetic stress and impaired physiological functioning • Increased mortality rates • Possible changes in reproductive phenology, including potential mismatches in reproductive timing and host fish presence	

Precipitation amount and drought

Changes in precipitation amount affect streamflow volume and velocity (Knowles et al. 2006; Meyers et al. 2010; Sawaske & Freyberg 2014; Power et al. 2016), with impacts on mussel species that vary by stream size (Hastie et al. 2003). Declines in precipitation affect mussels through reduced streamflow volume and associated increases in water temperature (Hastie et al. 2003), leading to loss of habitat for mussel recruitment and loss of habitat connectivity for host fish (Obedzinski et al. 2018). Periods of low precipitation reduce edge habitat near the banks of larger streams, allow mussel exposure to air, and promote accumulation of silt and debris in stream substrates (Hastie et al. 2003). Given their lower water volume and more exposed substrate, smaller streams tend to respond more quickly to flow changes than larger streams and rivers (Hastie et al. 2003). Small streams are also impacted more heavily during intense precipitation events that scour streambeds, dislodging mussels and reducing habitat suitability for juvenile settlement following substrate erosion (Hastie et al. 2001, 2003).

During periods of severe drought, reduced streamflow and associated increases in water temperature and decreases in dissolved oxygen can dramatically increase mussel mortality rates (Gagnon et al. 2004; Haag & Warren 2008; Shea et al. 2013). Drought impacts are particularly severe for mussels in smaller streams where flow reductions are typically more extreme (Haag & Warren 2008; Shea et al. 2013). In larger streams that maintain substantial flow, mussel abundance is less affected and mortality is concentrated in isolated areas at dry stream margins (Haag & Warren 2008). The ability of some species to move short distances in response to receding water levels (Vannote & Minshall 1982) may decrease drought-associated mortality for individual mussels (Golladay et al. 2004). This potential may be further limited by substrate, however, as mussels in cobble habitat or tucked in bedrock crevices are less able to move away from drying habitat. Winged/California floaters may also be more vulnerable to emersion due to the presence of this species in lowland areas where water levels are more likely to be heavily regulated. They also tend to be found in areas that dry more rapidly and where hyporheic flow does not occur (Vuln. Assessment Reviewer, pers. comm., 2019).

Historically, mussel populations in small streams that were reduced or eliminated by periodic drought likely rebounded relatively quickly due to immigration from downstream populations that were less affected by drought (Haag & Warren 2008). However, increased fragmentation of the landscape (i.e., through dams, water diversions, and in-stream culverts) increases the likelihood that drought will become a major threat to long-term viability of isolated headwater mussel communities (Haag & Warren 2008).

Regional Precipitation & Drought Trends	
Historical & current trends: • 2.6–9.4 cm (1.0–3.7 in) increase in mean annual precipitation between 1900 and 2009 for the Northwestern California, Southern Cascade, and Great Valley ecoregions (Rapacciuolo et al. 2014) • Drought years have occurred twice as often over the last two decades compared to the previous century (Diffenbaugh et al. 2015)	*Projected future trends:* • 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

Regional Precipitation & Drought Trends	
• 2012–2014 drought set records for lowest precipitation, highest temperatures, and most extreme drought indicators on record (Griffin & Anchukaitis 2014; Diffenbaugh et al. 2015)	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) • Drought years are twice as likely to occur over the next several decades due to increased co-occurrence of dry years with very warm years (Cook et al. 2015) • 80% chance of multi-decadal drought by 2100 under a high-emissions scenario (Cook et al. 2015) • Severe droughts that now occur once every 20 years will occur once every 10 years by 2100 and once-in-a-century drought will occur once every 20 years (Pierce et al. 2018)
Summary of Potential Impacts on Species Group *(see text for citations)*	
• Increased habitat elimination (from substrate scour and exposed habitat) and mussel dislodgement during heavy precipitation events • Degraded water quality and reduced areal extent of habitat during low precipitation periods • Increased thermal stress and mortality during low precipitation periods • Decreased juvenile recruitment due to accumulation of silt, sediment, and organic debris in substrate in the absence of significant precipitation	

Sensitivity and future exposure to changes in natural disturbance regimes

Regional experts evaluated native mussels as having low-moderate 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). The key natural disturbance regime that affects native mussels is flooding.[5]

---

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

[5] Disturbance regimes presented are those ranked as having a moderate or higher impact on this species group; additional changes in disturbance regimes that may influence the species group to a lesser degree include wildfire (particularly impacts related to erosion and sedimentation following severe fire in upland areas).

Flooding

Northern California rivers and streams are characterized by high winter and low summer flows, with biota adapted to high inter-annual flow variability, including periodic flooding (Power et al. 2016). Flooding plays an important role in riverine ecosystems by transporting sediment, importing large woody debris, and scouring floodplain soils (Reeves et al. 1995; Poff et al. 1997). However, severe flooding can degrade mussel habitat by scouring or aggrading streambeds and increasing sedimentation in rivers, streams, and lakes (Hastie et al. 2003). Flooding can also cause mussel injury or mortality due to stranding on river banks, damage from moving debris, or burial by gravel or sediment (Hastie et al. 2001). Although western pearlshell mussels in sandy substrates behind rocks and boulders are protected from some disturbances, more extreme flooding may dislodge individuals (Vannote & Minshall 1982). Severe flooding may also affect host fish populations through stranding, mortality, and loss of eggs and fry (National Marine Fisheries Service 2014, 2016).

Regional Flooding Trends	
Historical & current trends: • No trends available for flooding	*Projected future trends:* • 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)*	
• Increased injury and mortality from dislodgement and stranding • Increased sedimentation which could impair physiological functioning • Mortality and/or reduced reproductive success of host fish	

Dependency on habitat and/or other species

Regional experts evaluated native mussels as having low-moderate dependency on sensitive habitats (moderate confidence in evaluation), low dependency on prey or forage species (high confidence), and high dependency on host species abundance (e.g., salmonids; high confidence).

Freshwater mussels inhabiting rivers and streams in northern California, such as western pearlshell and western ridged mussels, are generally found in microhabitats that lessen the impacts of disturbance (e.g., scouring, burial; Vannote & Minshall 1982; Rempel et al. 2000; Howard & Cuffey 2003), provide a stable substrate and food supply, and increase chances of interactions with host fish to enhance reproductive success (Haag 2012). Because they have limited ability to move once settled, mussels are dependent on water movement in their habitat to provide food items (Haag 2012). Freshwater mussels are also highly dependent on host fish species to complete their reproduction cycle (Brim Box et al. 2006; O'Brien et al. 2013;

Maine et al. 2016). Although host fish data are incomplete, western pearlshell mussels appear to be heavily reliant on native salmonids (Blevins et al. 2017b), while western ridged mussels and winged/California floaters rely on inland or lake-dwelling fish (Brim Box et al. 2006; O'Brien et al. 2013; Maine et al. 2016). Several non-native fish species have also been documented as host species for native freshwater mussel species, including brown trout for the western pearlshell mussel (Murphy 1942) and green sunfish for the winged floater (Haley et al. 2007).

Sensitivity and current exposure to non-climate stressors

Regional experts evaluated native mussels as having high sensitivity to non-climate stressors (high confidence in evaluation), with an overall high current exposure to these stressors within the study region (high confidence). Key non-climate stressors that affect native mussels include dams and water diversions, pollution, and other stream sediment sources.[6]

Dams and water diversions

Construction and operation of dams for flood control, power generation, and water supply can degrade mussel habitat and lead to substantial declines in mussel populations (Haley et al. 2007; Richter & Thomas 2007). Dams artificially impound water, create rapid fluctuations in water levels, allow higher than normal flows, eliminate periodic scouring events that maintain channel complexity, and severely restrict flow (Haley et al. 2007; Richter & Thomas 2007; Vuln. Assessment Reviewer, pers. comm., 2019). A common impact of dam construction for mussels is a shift from lotic (flowing) to lentic (still water) environments after impoundment and a subsequent altering of mussel community composition to one more tolerant of slow or still water (Haag 2012).

Higher flow levels from dam operations can scour downstream habitat, disrupt reproduction, wash mussels downstream, and bury mussels under rocks, cobble, or sediment (Haag 2012; Davis et al. 2013; Blevins et al. 2017b). Unnatural pulses in stream discharge also have the potential to reduce downstream mussel reproductive success if such events occur during critical periods in the mussel reproductive cycle (Haley et al. 2007). For instance, pulsed high flows from dams in northern California can interfere with the reproductive success of western pearlshell and western ridged mussels by preventing the settlement of juvenile mussels into the substrate (Haley et al. 2007; Richter & Thomas 2007). Conversely, flow restrictions from dam operations can result in the drying of river and stream edges that are usually suitable for mussel occupancy during normal flow conditions (Davis et al. 2013). Low-flow conditions also increase stream water temperature, expose mussels to air, and lead to accumulation of silt and debris in stream substrates (Hastie et al. 2003; Davis et al. 2013). In California, western pearlshell mussels are particularly threated by water diversion projects for irrigation, power generation, and water supply that restrict streamflow (Kanz 2008; Norgaard et al. 2016).

Although little research is available, dams also impact freshwater mussels by interfering with host fish movement (Bogan 1993; Blevins et al. 2017a). By restricting their movement, dams

---

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

can reduce or extirpate host fish species such as salmonids from mussel habitat, especially in higher elevation streams, leading to rapid declines in mussel populations when combined with other stressors (Bogan 1993). Over the longer term, disruption of host fish migration can lead to lower genetic diversity in mussel populations upstream of dams (Mock et al. 2010).

Dams also decrease water quality in mussel habitats in northern California (Davis et al. 2013). Four dams currently block the flow of the Klamath River, impounding warm, nutrient-rich water that produces blooms of hepatotoxic blue-green algae (*Microcystis aeruginosa*) in the summer (Davis et al. 2013). This condition is acute at the Iron Gate and Copco Reservoirs where *M. aeruginosa* decay reduces dissolved oxygen in mussel habitat (Kann & Corum 2006; Karuk DNR 2009; Davis et al. 2013). Water quality improves for downstream mussel habitat as major tributaries provide large freshwater inputs that increase dissolved oxygen and reduce nutrient and toxin concentrations (Karuk DNR 2009; Asarian et al. 2010).

Pollution

Pollution is widespread in freshwater mussel habitats in northern California (Naimo 1995; Bettaso & Goodman 2010; Norgaard et al. 2013). Given that they are primarily sessile, long-lived, and have life history strategies that include burrowing in sediment and filter feeding, freshwater mussels bioaccumulate contaminants to a greater degree than many other aquatic fauna (Havlik & Marking 1987; Cope et al. 2008; Haag 2012). As a result, they are often among the first species to respond to water quality degradation (Havlik & Marking 1987; Haag 2012). Contaminants can reduce freshwater mussel populations through direct mortality or by impacting biological functions, behavior, host fish mortality, or food availability (Havlik & Marking 1987; Cope et al. 2008).

A major source of pollution in mussel habitat is contaminants from historic and contemporary mining practices (Harvey & Lisle 1998; Bettaso & Goodman 2010; Norgaard et al. 2013). For instance, in the Klamath River and its tributaries, western ridged mussels are accumulating high levels of lead, cadmium, and tin (Norgaard et al. 2013), while western pearlshell mussels in the Trinity River have exhibited high mercury levels (Bettaso & Goodman 2010). Activities such as dredging can mobilize legacy mercury and other toxic heavy metals downstream of historical mining sites (Salomons et al. 1987; Harvey & Lisle 1998). Long-range transport of air pollution from outside the region can also deposit heavy metals, including cadmium and mercury, into aquatic habitats (Norton et al. 1990).

Other sources of pollution in freshwater mussel habitats includes agricultural runoff, which increases ammonia levels and can lead to reproductive failure (Strayer & Malcolm 2012). Livestock grazing in riparian areas can also result in nitrogen pollution that increases eutrophication, lowering dissolved oxygen levels and subsequently reducing mussel fitness and functioning (Belsky et al. 1999; Haag 2012).

Other stream sediment sources

Freshwater mussels are highly sensitive to excessive sedimentation, which can alter biological functioning and habitat substrate properties (Brim Box & Mossa 1999). Excessive sediments, especially fine particles, that wash into rivers and streams can reduce interstitial flow rates near settled mussels (Brim Box & Mossa 1999) and interfere with filter feeding (Tuttle-Raycraft et al. 2017). Indirectly, increased stream sedimentation impacts the production of mussel food items by reducing light available for photosynthesis (Kanehl & Lyons 1992). As a result, sediment can have major impacts on mussels' physical functioning, lessening their ability to take in oxygen, excrete nitrogen, and filter water, potentially resulting in starvation or semi-starvation in environments with high levels of suspended sediments (Brim Box & Mossa 1999).

Although dams and water diversions are among the most significant sources of sediment and debris in mussel habitat, other sources can include mining (Krueger et al. 2007), stream channelization/dredging, and restoration activities (Haag 2012; Blevins et al. 2017b). Instream gravel mining removes substrate and increases downstream siltation (Bogan 1993), which can compromise mussel functioning and increase mortality (Brim Box & Mossa 1999). Suction dredge mining can also kill western pearlshell mussels by covering them with tailings from which they cannot extricate themselves (Krueger et al. 2007). Dredging, channelization, and livestock grazing in riparian areas can lead to stream headcutting (i.e., an abrupt change in bed surface elevation where intense, localized erosion occurs; Alonso et al. 2002), which causes sedimentation in mussel habitat (Hartfield 1993) and direct mortality of mussels (Haag 2012).

Finally, activities such as culvert removal, dam removal, and stream reconfiguration to restore aquatic habitat for salmonids can cause a sudden increase in downstream sediment supply that may impact mussels, particularly if consideration is not given to mussel distribution or life history requirements (Haag 2012; Blevins et al. 2017b). For instance, increased sedimentation from habitat restoration activities can affect the survival of downstream mussel populations, especially in conjunction with temporary stream dewatering and movement of personnel and equipment in streams (Haag 2012; Blevins et al. 2017b).

Adaptive Capacity

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

Species group extent, integrity, connectivity, and dispersal ability

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

Regional experts evaluated native mussels as having a low dispersal ability (low confidence in evaluation). Barriers to dispersal were evaluated as having a low-moderate impact on the species group (moderate confidence). Dependency on salmonids for dispersal was identified as the primary barrier to dispersal.

North American freshwater mussel populations have declined over the past century due to historic overharvesting, habitat destruction, and pollution (Haag 2012). Between historic (pre-1990) and recent time periods, western pearlshell mussel populations declined by 17% range-wide and by 22.5% in California (Blevins et al. 2017a). Within the state, northern California serves as a refugia for mussel populations that have been reduced or extirpated from southern California, although population declines are still occurring in this area of the state (Howard et al. 2015b).

Part of the dramatic decline in freshwater mussel species throughout North America (Lydeard et al. 2004) is attributable to life history traits that make mussels sensitive to climate and non-climate stressors and their limited ability to move to new habitats in response to disturbances or exteme events (Galbraith et al. 2010; Inoue & Berg 2017). Given their sessile lifestyle, freshwater mussel populations are expected to become increasingly fragmented (Inoue & Berg 2017) and experience greater impacts from habitat modification and/or loss than other aquatic fauna (Markovic et al. 2014). Mussel dispersal opportunties are limited by the factors that affect the migration of anadromous and inland host fish species, including physical barriers (e.g., dams, culverts) and physiological barriers (e.g., low flows, thermal blocks) , and habitat modifications that render areas unsuitable for host fish life stages (e.g., stream channelization, stream sedimentation; (Katz et al. 2013; National Marine Fisheries Service 2014, 2016; Vuln. Assessment Reviewer, pers. comm., 2019). Habitat modifications may also make areas unsuitable for mussels, so even if they are able to reproduce and disperse they may not persist where they land after dispersal (Vuln. Assessment Reviewer, pers. comm., 2019).

Host fish habitat is also becoming increasingly fragmented (Moyle et al. 2013; National Marine Fisheries Service 2014, 2016), and host fish abundance in mussel habitat may influence future freshwater mussel distributional patterns more than any other factor (Pandolfo et al. 2012; Schwalb et al. 2013). Once anadromous host fish are extirpated from a watershed, it is highly unlikely that mussels will reoccupy that watershed without management intervention (Vuln. Assessment Workshop, pers. comm., 2017).

Intraspecific/life history diversity

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

While all freshwater mussels are relatively sessile and require host fish for reproduction, other life history characteristics are highly variable between species (Vuln. Assessment Reviewer, pers. comm., 2019). Differences in shell morphology, shell thickness, and other factors enable mussels to tolerate varying hydrological and substrate conditions (Stanley 1981; Allen & Vaughn 2010; Hornbach et al. 2010) and likely contribute to patterns of species distribution (Davis et al. 2013). The ability to adapt glochidia release to water temperatures (Murphy 1942; Haag 2012; O'Brien et al. 2013; Allard et al. 2015) and variable growth and age to reproduction depending on environmental conditions also afford freshwater mussels a relatively high level of plasticity

(Vuln. Assessment Reviewer, pers. comm., 2019). Additionally, western pearlshell mussels can exhibit hermaphroditism (Heard 1970; Chong et al. 2009), which would suggest higher life history diversity and behavioral plasticity in this species. However, both western pearlshell and western ridged mussels have high host specificity, reducing life history plasticity in these species compared to host fish generalists such as California/winged floaters (Vuln. Assessment Reviewer, pers. comm., 2019). Genetic diversity is likely also higher in California/winged floaters compared to western pearlshell and western ridged mussels, and appears to show watershed level structure in northern California (Mock et al. 2013).

Freshwater mussels are fairly limited in their ability to respond to many external factors, but they do have some ability to adapt to some changes in environmental conditions by altering their burrowing, filtering, and reproductive behavior (Archambault et al. 2013; Vuln. Assessment Reviewer, pers. comm., 2019).

Resistance and recovery

Regional experts evaluated native mussels as having low resistance to climate stressors and natural disturbance regimes (high confidence in evaluation). Recovery potential was evaluated as low (high confidence).

In northern California, riverine mussels have evolved with the variable disturbance regimes characteristic of aquatic habitats in a Mediterranean climate, including fluctuating streamflows, variable precipitation, and periodic drought and heat waves (Davis et al. 2013; Howard et al. 2015a). However, freshwater mussel populations recover very slowly from disturbances, due largely to their slow sexual maturity and inability to disperse to new habitat as adults (Galbraith et al. 2010). The continued decline in abundance and range contractions observed in freshwater mussels (Howard et al. 2015b; Blevins et al. 2017a) suggest that they have relatively low resistance to increasing rates of climatic change, extreme events, and/or anthropogenic disturbances (Davis et al. 2013; Archambault et al. 2018). Juvenile mussels are especially vulnerable to disturbances before they settle in the substrate (Haley et al. 2007; Krueger et al. 2007; Irmscher & Vaughn 2018) and may also be more vulnerable to pollution than adult mussels (Cope et al. 2008).

Management potential

Public and societal value

Regional experts evaluated native mussels as having low-moderate public and societal value (high confidence in evaluation).

Freshwater mussels have been highly valued by Pacific Northwest tribes for more than 10,000 years (Osborne 1951; Lyman 1984; Haag 2012; Confederated Tribes of the Umatilla Indian Reservation 2015). Native freshwater mussels have strong cultural significance for northern California tribes, and are utilized for subsistence, ornamental, and ceremonial purposes (Driver 1939; Anderson 2005; Norgaard 2005; Davis et al. 2013; Norgaard et al. 2013, 2016; Sloan & Hostler 2014). In the last century, northern California tribes have been denied access to manage mussel populations in tribal lands, and mussels in these areas have been degraded by stressors outside of tribal control (e.g., reduced flows, contamination, fishing restrictions, non-tribal resource consumption; Norgaard 2005). Denial of management control over mussel beds limits access to an important food source by tribal members and eliminates a traditional cultural practice (Norgaard 2005).

Although researchers have a good understanding of the threats mussels face, there is limited information on the specific outcomes resulting from management activities and decisions (Vuln. Assessment Reviewer, pers. comm., 2019). For instance, although elevated total suspended solids is known to harm mussels (Tuttle-Raycraft et al. 2017), there is currently no minimum accepted level of TSS loads that will protect mussels. Additionally, there are few conservation initiatives that support freshwater mussels (Vuln. Assessment Workshop, pers. comm. 2017). None of the three freshwater mussel species in northern California are state- or federally listed as threatened or endangered (Kanz 2008), although the California floater has been petitioned for federal listing in the past (Vuln. Assessment Reviewer, pers. comm., 2019). Although it doesn't provide policy protection, all species considered in this assessment are identified as species of greatest conservation need in the 2015 California State Wildlife Action Plan (CDFW 2015).

There is more widespread awareness in the public about threats to salmonid host fish due to their high public and cultural value (Karuk Tribe Department of Natural Resources 2009; Norgaard et al. 2016; Vuln. Assessment Workshop, pers. comm., 2017), and several mussel host species in northern California have recovery plans owing to their listing as federally threatened species (National Marine Fisheries Service 2014, 2016). Societal support for management of host fish populations, such as regulatory support for anadromous fish population recovery, could also enhance mussel population recovery efforts (Blevins et al. 2017b). Conversely, preserving existing mussel beds maintains ecosystem services and maximizes the benefits of fish-focused restoration efforts as well (Blevins et al. 2017b). In general, anadromous fish have greater societal awareness and value than inland fish species (Lynch et al. 2016), which also serve as host fish for mussels (Haley et al. 2007; O'Brien et al. 2013; Maine et al. 2016).

Enforcement of the federal Clean Water Act and adoption of water quality criteria that protect streams regardless of the presence of mussels can result in improved water quality, supporting existing populations and potentially allowing recolonization of former habitat (Sietman et al. 2001; Strayer et al. 2004; Vuln. Assessment Reviewer, pers. comm., 2019). In addition, dams in California are subject to Section 5937 of the California Fish and Game Code that requires owners of dam to allow sufficient water to pass through a fishway or over, around, or through a dam to support fish and mollusks that exist below the dam (Kanz 2008; Bork et al. 2011).

Management capacity and ability to alleviate impacts[7]
Regional experts evaluated the potential for reducing climate impacts on native mussels through management as moderate (moderate confidence in evaluation).

There are multiple approaches to rebuild and preserve healthy freshwater mussel populations in northern California, primarily by addressing hydrologic regime changes, habitat impacts, and water quality degradation (Davis et al. 2013; Blevins et al. 2017b), while also addressing the challenges presented by small populations and reduced genetic diversity (Archambault et al. 2018). Many management options that support anadromous host fish survival and reproduction in a changing climate would likely also increase mussel abundance and fitness (e.g., reducing water withdrawals; Vuln. Assessment Reviewer, pers. comm., 2019). However, some restoration projects designed to benefit fish can degrade mussel habitat or directly harm mussel populations, which require permanently inundated habitat and a stable substrate for burrowing (Blevins et al. 2017b). Incorporating best management practices into aquatic and riparian restoration projects could help prevent the further decline of freshwater mussels in the region (Blevins et al. 2017b).

Management actions that may directly or indirectly increase mussel populations, preserve/restore mussel habitat, and benefit anadromous and inland host fish species include:

- *Protect and/or restore existing mussel habitat*—Because mussels are sessile and recovery of disturbed populations is very slow, it is vital to consider the unique life history and habitat needs of freshwater mussels when carrying out restoration projects designed to benefit native fish or general ecosystem functioning (Blevins et al. 2017b). Restoration opportunities specifically meant to improve mussel habitat might include the design of stabilizing features and burrowing habitat (Blevins et al. 2017b). Protecting existing mussel beds could further improve habitat and water quality, potentially reducing the effects of climate impacts beyond a single population or species (Blevins et al. 2017b).
- *Managing dams and water withdrawals to restore natural hydrology*— Managing dam operations in synchrony with mussel reproductive periods could help maintain mussel populations under changing hydrologic regimes (Richter & Thomas 2007; Galbraith et al. 2010; Haag 2012). For instance, pulsed flows for channel maintenance and/or recreation could be timed to occur late enough that they do not interfere with mussel reproduction and the successful settlement of juvenile mussels (Haley et al. 2007). Maintaining dam releases during periods of drought may also alleviate some of the impacts of low flows on mussel populations, preventing population declines that would otherwise occur (Allen et al. 2013).
- *Considering landscape-scale factors to refine knowledge of mussel distribution and inform management efforts*—Because mussel populations and habitats are both heterogeneous and fragmented, researchers suggest considering factors that influence mussel distribution at multiple spatial scales to design effective mussel habitat

---

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

management actions (Newton et al. 2008). For instance, considering hydrology, stream bank type, and substrate stability can highlight priority areas for mussel habitat and restoration efforts (Davis et al. 2013).

- *Continuing research on life history and distribution information to support mussel conservation and potential translocation actions*—Multiple researchers highlight the need for more basic research on freshwater mussels in the western U.S. (Blevins et al. 2017a, 2017b; Archambault et al. 2018), especially distribution, dispersal, reproduction, genetics, host-fish interactions, and behavior (Barnhart et al. 2008; Spooner & Vaughn 2008). Researchers could also study the characteristics of sites in northern California where freshwater mussels are still abundant to determine which habitat characteristics have led to the success of these populations (Vuln. Assessment Reviewer, pers. comm., 2019). This information is needed to guide management decisions that will become more pressing in a changing climate, including population augmentation and translocation (Barnhart et al. 2008; Spooner & Vaughn 2008).

Ecosystem services

Native freshwater mussels provide a variety of ecosystem services, including:

- Provisioning of food (i.e., to people and wildlife), shells (i.e., for tools, jewelry, and art);
- Regulation of water purification (biofiltration);
- Support of nutrient cycling/storage, habitat structure, substrate and food web modification, and environmental monitoring; and
- Cultural/tribal uses for spiritual/religious purposes, knowledge systems, educational values, aesthetic values, social relations, sense of place, inspiration, and cultural heritage (Haag 2012; Confederated Tribes of the Umatilla Indian Reservation 2015; Vuln. Assessment Workshop, pers. comm., 2017; Vaughn 2018; Vaughn & Hoellein 2018).

Mussels are excellent biological indicators of ecosystem health due to their long lives and high sensitivity to environmental changes (Haag 2012; Vaughn 2018; Vaughn & Hoellein 2018). Because they are sessile filter feeders, freshwater mussels improve water quality by removing solids, nutrients, and contaminants from the water column (Vaughn 2018; Vaughn & Hoellein 2018). Mussels also cycle nutrients that feed benthic macroinvertebrates and other aquatic organisms, increasing biomass and biodiversity within mussel habitat (Vaughn 2018; Vaughn & Hoellein 2018). Finally, mussels are an important food source for a variety of wildlife, including fish, turtles, raccoons, muskrats, and wading birds (Haag 2012).

Recommended Citation

Sims, SA, Hilberg LE, Reynier WA, Kershner JM. 2019. Native Freshwater Mussels: Northern California Climate Change Vulnerability Assessment Synthesis. Version 1.0. EcoAdapt, Bainbridge Island, WA.

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.

Allard DJ, Whitesel TA, Lohr S, Koski ML. 2015. Western pearlshell mussel life history in Merrill Creek, Oregon: reproductive timing, growth, and movement. U.S. Fish and Wildlife Service, Columbia River Fisheries Program Office, Vancouver, WA.

Allen DC, Galbraith HS, Vaughn CC, Spooner DE. 2013. A tale of two rivers: implications of water management practices for mussel biodiversity outcomes during droughts. Ambio **42**:881–891.

Allen DC, Vaughn CC. 2010. Complex hydraulic and substrate variables limit freshwater mussel species richness and abundance. Journal of the North American Benthological Society **29**:383–394.

Alonso CV, Bennett SJ, Stein OR. 2002. Predicting head cut erosion and migration in concentrated flows typical of upland areas. Water Resources Research **38**:1303.

Anderson MK. 2005. Tending the wild: Native American knowledge and the management of California's natural resources. University of California Press, Berkeley, CA.

Archambault JM, Cope WG, Kwak TJ. 2013. Burrowing, byssus, and biomarkers: behavioral and physiological indicators of sublethal thermal stress in freshwater mussels (Unionidae). Marine and Freshwater Behaviour and Physiology **46**:229–250.

Archambault JM, Cope WG, Kwak TJ. 2018. Chasing a changing climate: reproductive and dispersal traits predict how sessile species respond to global warming. Diversity and Distributions **24**:880–891.

Asarian E, Kann J, Walker W. 2010. Klamath River nutrient loading and retention dynamics in free-flowing reaches, 2005–2008. Final Technical Report to the Yurok Tribe Environmental Program. Yurok Tribe, Klamath, CA.

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.

Barnhart MC, Haag WR, Roston WN. 2008. Adaptations to host infection and larval parasitism in Unionoida. Journal of the North American Benthological Society **27**:370–394.

Belsky AJ, Matzke A, Uselman S. 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water Conservation **54**:419–431.

Bettaso JB, Goodman DH. 2010. A comparison of mercury contamination in mussel and ammocoete filter feeders. Journal of Fish and Wildlife Management **1**:142–145.

Black BA, Dunham JB, Blundon BW, Brim-Box J, Tepley AJ. 2015. Long-term growth-increment chronologies reveal diverse influences of climate forcing on freshwater and forest biota in the Pacific Northwest. Global Change Biology **21**:594–604.

Black BA, Dunham JB, Blundon BW, Raggon MF, Zima D. 2010. Spatial variability in growth-increment chronologies of long-lived freshwater mussels: implications for climate impacts and reconstructions. Ecoscience **17**:240–250.

Blevins E. 2018. Opportunities for freshwater mussel conservation in the Pacific Northwest and Intermountain West in a changing climate. Unpublished report. The Xerces Society for Invertebrate Conservation, Portland, OR.

Blevins E, Jepsen S, Brim Box JC, Nez D, Howard J, Maine A, O'Brien C. 2017a. Extinction risk of western North American freshwater mussels: *Anodonta nuttalliana*, the *Anondonta*

Oregonensis/Kennerlyi clade, *Gonidea angulata*, and *Margaritifera falcata*. Freshwater Mollusk Biology and Conservation **20**:71.

Blevins E, McMullen L, Jepsen S, Blackburn M, Code A, Scott Hoffman Black. 2017b. Conserving the gems of our waters: best management practices for protecting native western freshwater mussels during aquatic and riparian restoration, construction, and land management projects and activities. The Xerces Society for Invertebrate Conservation, Portland, OR. Available from https://xerces.org/conserving-the-gems-of-our-waters/ (accessed March 11, 2019).

Bogan AE. 1993. Freshwater bivalve extinctions (Mollusca: Unionoida): a search for causes. American Zoologist **33**:599–609.

Bork KS, Krovoza JF, Katz JV, Moyle PB. 2011. The rebirth of California Fish & Game Code Section 5937: water for fish. 45 U.C.D. L. Rev. 809 (2011-2012).

Brim Box JC, Howard J, Wolf D, O'Brien C, Nez D, Close D. 2006. Freshwater mussels (Bivalvia: Unionoida) of the Umatilla and Middle Fork John Day rivers in eastern Oregon. Northwest Science **80**:95–107.

Brim Box JC, Mossa J. 1999. Sediment, land use, and freshwater mussels: prospects and problems. Journal of the North American Benthological Society **18**:99–117.

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.

Chen L-Y, Heath AG, Neves RJ. 2001. Comparison of oxygen consumption in freshwater mussels (Unionidae) from different habitats during declining dissolved oxygen concentration. Hydrobiologia **450**:209–214.

Chong JP, Brim Box JC, Howard JK, Wolf D, Myers TL, Mock KE. 2009. Three deeply divided lineages of the freshwater mussel genus Anodonta in western North America. Conservation Genetics **9**:1303–1309.

Christian AD, Smith BN, Berg DJ, Smoot JC, Findlay RH. 2004. Trophic position and potential food sources of 2 species of unionid bivalves (Mollusca: Unionidae) in 2 small Ohio streams. Journal of the North American Benthological Society **23**:101–113.

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.

Confederated Tribes of the Umatilla Indian Reservation. 2015. Saxu Siwala Seewis: river mussels through time. Color Press Publishing, Walla Walla, WA.

Cook BI, Ault TR, Smerdon JE. 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. Science Advances **1**:e1400082.

Cope WG, Bringolf RB, Buchwalter DB, Newton TJ, Ingersoll CG, Wang N, Augspurger T, Dwyer FJ, Barnhart MC, Neves RJ. 2008. Differential exposure, duration, and sensitivity of unionoidean bivalve life stages to environmental contaminants. Journal of the North American Benthological Society **27**:451–462.

Davis EA, David AT, Norgaard KM, Parker TH, McKay K, Tennant C, Soto T, Rowe K, Reed R. 2013. Distribution and abundance of freshwater mussels in the mid Klamath Subbasin, California. Northwest Science **87**:189–206.

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.

Dettinger MD, Ralph FM, Das T, Neiman PJ, Cayan DR. 2011. Atmospheric rivers, floods and the water resources of California. Water **3**:445–478.

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.

Driver HE. 1939. Culture element distributions: X northwest California. University of California Anthropological Records **1**:297–433.

Fang X, Stefan HG. 2009. Simulations of climate effects on water temperature, dissolved oxygen, and ice and snow covers in lakes of the contiguous US under past and future climate scenarios. Limnology and Oceanography **54**:2359–2370.

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.

Furnish J. 2007. Guide to sensitive aquatic mollusks of the U.S. Forest Service Pacific Southwest Region. U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, Vallejo, CA.

Gagnon PM, Golladay SW, Michener WK, Freeman MC. 2004. Drought responses of freshwater mussels (Unionidae) in coastal plain tributaries of the Flint River basin, Georgia. Journal of Freshwater Ecology **19**:667–679.

Galbraith HS, Spooner DE, Vaughn CC. 2010. Synergistic effects of regional climate patterns and local water management on freshwater mussel communities. Biological Conservation **143**:1175–1183.

Golladay SW, Gagnon P, Kearns M, Battle JM, Hicks DW. 2004. Response of freshwater mussel assemblages (Bivalvia: Unionidae) to a record drought in the Gulf Coastal Plain of southwestern Georgia. Journal of the North American Benthological Society **23**:494–506.

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.

Haag WR. 2012. North American freshwater mussels: natural history, ecology, and conservation. Cambridge University Press, New York, NY.

Haag WR, Warren ML Jr. 2008. Effects of severe drought on freshwater mussel assemblages. Transactions of the American Fisheries Society **137**:1165–1178.

Haley L, Ellis M, Cook J. 2007. Reproductive timing of freshwater mussels and potential impacts of pulsed flows on reproductive success. CEC-500-2007-097. Prepared for: California Energy Commission Public Interest Energy Research Program. Spring Rivers Ecological Sciences, LLC, Cassel, CA.

Hartfield P. 1993. Headcuts and their effect on freshwater mussels. Pages 131–141 in K. S. Cummings, A. C. Buchanan, and L. M. Koch, editors. Conservation and management of freshwater mussels. Proceedings of a UMRCC Symposium, October 1992, St Louis. MO. Upper Mississippi River Conservation Committee, Rock Island, IL.

Harvey BC, Lisle TE. 1998. Effects of suction dredging on streams: a review and an evaluation strategy. Fisheries **23**:8–17.

Hastie LC, Boon PJ, Young MR, Way S. 2001. The effects of a major flood on an endangered freshwater mussel population. Biological Conservation **98**:107–115.

Hastie LC, Cosgrove PJ, Ellis N, Gaywood MJ. 2003. The threat of climate change to freshwater pearl mussel populations. Ambio **32**:40–46.

Havlik ME, Marking LL. 1987. Effects of contaminants on naiad mollusks (Unionidae): a review. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C.

Heard WH. 1970. Hermaphroditism in *Margaritifera falcata* (Gould) (Pelecypoda: Margaritiferidae). Nautilus **83**:113–114.

Hornbach DJ, Kurth VJ, Hove MC. 2010. Variation in freshwater mussel shell sculpture and shape along a river gradient. The American Midland Naturalist **164**:22–36.

Howard JK et al. 2015a. Patterns of freshwater species richness, endemism, and vulnerability in California. PLoS ONE **10**:e0130710.

Howard JK, Cuffey KM. 2003. Freshwater mussels in a California North Coast Range river: occurrence, distribution, and controls. Journal of the North American Benthological Society **22**:63–77.

Howard JK, Cuffey KM. 2006. The functional role of native freshwater mussels in the fluvial benthic environment. Freshwater Biology **51**:460–474.

Howard JK, Furnish JL, Brim Box JC, Jepsen S. 2015b. The decline of native freshwater mussels (Bivalvia: Unionoida) in California as determined from historical and current surveys. California Fish and Game **101**:8–23.

Inoue K, Berg DJ. 2017. Predicting the effects of climate change on population connectivity and genetic diversity of an imperiled freshwater mussel, *Cumberlandia monodonta* (Bivalvia: Margaritiferidae), in riverine systems. Global Change Biology **23**:94–107.

Irmscher P, Vaughn CC. 2018. Effects of juvenile settling and drift rates on freshwater mussel dispersal. The American Midland Naturalist **180**:258–272.

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.

Isaak DJ, Wollrab S, Horan D, Chandler G. 2012. Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes. Climatic Change **113**:499–524.

Isaak DJ, Young MK, Luce CH, Hostetler SW, Wenger SJ, Peterson EE, Hoef JMV, Groce MC, Horan DL, Nagel DE. 2016. Slow climate velocities of mountain streams portend their role as refugia for cold-water biodiversity. Proceedings of the National Academy of Sciences **113**:4374–4379.

Kanehl PD, Lyons JD. 1992. Impacts of in-stream sand and gravel mining on stream habitat and fish communities, including a survey on the Big Rib River, Marathon County, Wisconsin. Research Report 155. Wisconsin Department of Natural Resources, Monona, WI.

Kann J, Corum S. 2006. Summary of 2005 toxic *Microcystin aeruginosa* trends in Copco and Iron Gate Reservoirs on the Klamath River. Prepared by Aquatic Ecosystem Sciences and the Karuk Tribe Department of Natural Resources for the Karuk Tribe, Orleans, CA.

Kanz R. 2008. Status of Freshwater Mussels. California Water Resources Control Board, Division of Water Rights, Sacramento, CA.

Karna DW, Millemann RE. 1978. Glochidiosis of salmonid fishes. III. Comparative susceptibility to natural infection with *Margaritifera margaritifera* (L.) (Pelecypoda: Margaritanidae) and associated histopathology. The Journal of Parasitology **64**:528–537.

Karuk DNR. 2009. Eco-cultural resources management plan. Karuk Tribe Department of Natural Resources, Orleans, CA.

Katz J, Moyle PB, Quiñones RM, Israel J, Purdy S. 2013. Impending extinction of salmon, steelhead, and trout (Salmonidae) in California. Environmental Biology of Fishes **96**:1169–1186.

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.

Knowles N, Dettinger MD, Cayan DR. 2006. Trends in snowfall versus rainfall in the western United States. Journal of Climate **19**:4545–4559.

Krueger K, Chapman P, Hallock M, Quinn T. 2007. Some effects of suction dredge placer mining on the short-term survival of freshwater mussels in Washington. Northwest Science **81**:323–332.

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.

Lydeard C, Cowie RH, Ponder WF, Bogan AE, Bouchet P, Clark SA, Cummings KS, Frest TJ, Gargominy O, Herbert DG. 2004. The global decline of nonmarine mollusks. AIBS Bulletin **54**:321–330.

Lyman RL. 1984. A model of large freshwater clam exploitation in the prehistoric Southern Columbia Plateau culture area. Northwest Anthropological Research Notes **18**:97–107.

Lynch AJ et al. 2016. The social, economic, and environmental importance of inland fish and fisheries. Environmental Reviews **24**:115–121.

Maine A, Arango C, O'Brien C. 2016. Host fish associations of the California Floater (*Anodonta californiensis*) in the Yakima River Basin, Washington. Northwest Science **90**:290–300.

Markovic D, Carrizo S, Freyhof J, Cid N, Lengyel S, Scholz M, Kasperdius H, Darwall W. 2014. Europe's freshwater biodiversity under climate change: distribution shifts and conservation needs. Diversity and Distributions **20**:1097–1107.

Meyers EM, Dobrowski B, Tague CL. 2010. Climate change impacts on flood frequency, intensity, and timing may affect trout species in Sagehen Creek, California. Transactions of the American Fisheries Society **139**:1657–1664.

Meyers TR, Millemann RE. 1977. Glochidiosis of salmonid fishes. I. Comparative susceptibility to experimental infection with *Margaritifera margaritifera* (L.)(Pelecypoda: Margaritanidae). The Journal of Parasitology **63**:728–733.

Micheli E, Dodge C, Flint L, Comendant T. 2018. Climate and natural resource analyses and planning for the North Coast Resource Partnership: a technical memorandum summarizing data products. A final report prepared by the Dwight Center for Conservation Science at Pepperwood, Santa Rosa, CA, for West Coast Watershed and the North Coast Resource Partnership.

Mock KE, Brim Box JC, Chong JP, Furnish JL, Howard JK. 2013. Comparison of population genetic patterns in two widespread freshwater mussels with contrasting life histories in western North America. Molecular Ecology **22**:6060–6073.

Mock KE, Brim Box JC, Chong JP, Howard JK, Nez DA, Wolf D, Gardner RS. 2010. Genetic structuring in the freshwater mussel *Anodonta* corresponds with major hydrologic basins in the western United States. Molecular Ecology **19**:569–591.

Moyle PB, Kiernan JD, Crain PK, Quiñones RM. 2013. Climate change vulnerability of native and alien freshwater fishes of California: a systematic assessment approach. PLoS ONE **8**:e63883.

Murphy G. 1942. Relationship of the fresh-water mussel to trout in the Truckee River. California Fish and Game **28**:89–102.

Naimo TJ. 1995. A review of the effects of heavy metals on freshwater mussels. Ecotoxicology **4**:341–362.

National Marine Fisheries Service. 2014. Final recovery plan for the southern Oregon/northern California coast evolutionarily significant unit of coho salmon (*Oncorhynchus kisutch*). National Marine Fisheries Service, West Coast Region, Arcata, CA.

National Marine Fisheries Service. 2016. Final coastal multispecies recovery plan. National Marine Fisheries Service, West Coast Region, Santa Rosa, CA.

Newton TJ, Woolnough DA, Strayer DL. 2008. Using landscape ecology to understand and manage freshwater mussel populations. Journal of the North American Benthological Society **27**:424–439.

Nichols SJ, Garling D. 2000. Food-web dynamics and trophic-level interactions in a multispecies community of freshwater unionids. Canadian Journal of Zoology **78**:871–882.

Nichols SJ, Silverman H, Dietz TH, Lynn JW, Garling DL. 2005. Pathways of food uptake in native (Unionidae) and introduced (Corbiculidae and Dreissenidae) freshwater bivalves. Journal of Great Lakes Research **31**:87–96.

Nielsen JL, Lisle TE, Ozaki V. 1994. Thermally stratified pools and their use by steelhead in northern California streams. Transactions of the American Fisheries Society **123**:613–626.

Norgaard KM. 2005. The effects of altered diet on the health of the Karuk people. Submitted to Federal Energy Regulatory Commission, Docket# P-2082 on Behalf of the Karuk Tribe of California. Available from https://www.klamathwaterquality.com/documents/Norgaard_%20Health%20Effects%20of%20Altered%20Diet.pdf (accessed September 29, 2017).

Norgaard KM, Meeks S, Crayne B, Dunnivant F. 2013. Trace metal analysis of Karuk traditional foods in the Klamath River. Journal of Environmental Protection **4:319–328**.

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.

Norton SA, Dillon PJ, Evans RD, Mierle G, Kahl JS. 1990. The history of atmospheric deposition of Cd, Hg, and Pb in North America: evidence from lake and peat bog sediments. Pages 73–102 in S. E. Lindberg, A. L. Page, and S. A. Norton, editors. Acidic precipitation. Advances in Environmental Science, Vol 3. Springer, New York, NY.

Obedzinski M, Pierce SN, Horton GE, Deitch MJ. 2018. Effects of flow-related variables on oversummer survival of juvenile coho salmon in intermittent streams. Transactions of the American Fisheries Society **147**:588–605.

O'Brien C, Nez D, Wolf D, Box JB. 2013. Reproductive biology of *Anodonta californiensis*, *Gonidea angulata*, and *Margaritifera falcata* (Bivalvia: Unionoida) in the Middle Fork John Day River, Oregon. Northwest Science **87**:59–73.

Osborne HD. 1951. Excavations near Umatilla, Oregon: The archaeology of the Columbia intermontane province. University of California, Berkeley, Berkeley, CA.

Pandolfo TJ, Cope WG, Arellano C, Bringolf RB, Barnhart MC, Hammer E. 2010. Upper thermal tolerances of early life stages of freshwater mussels. Journal of the North American Benthological Society **29**:959–969.

Pandolfo TJ, Kwak TJ, Cope WG. 2012. Thermal tolerances of freshwater mussels and their host fishes: species interactions in a changing climate. Walkerana **15**:69–82.

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.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime. BioScience **47**:769–784.

Power ME, Kupferberg SJ, Cooper SD, Deas ML, Hamey N, Powell R, Swiers R. 2016. Rivers. Pages 713–752 in H. Mooney and E. Zavaleta, editors. Ecosystems of California. University of California Press, Oakland, CA.

Rapacciuolo G et al. 2014. Beyond a warming fingerprint: individualistic biogeographic responses to heterogeneous climate change in California. Global Change Biology **20**:2841–2855.

Reeves GH, Benda LE, Burnett KM, Bisson PA, Sedell JR. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. American Fisheries Society Symposium. **17**:334–349.

Rempel LL, Richardson JS, Healey MC. 2000. Macroinvertebrate community structure along gradients of hydraulic and sedimentary conditions in a large gravel-bed river. Freshwater biology **45**:57–73.

Richter BD, Thomas GA. 2007. Restoring environmental flows by modifying dam operations. Ecology and society **12**.

Salomons W, De Rooij NM, Kerdijk H, Bril J. 1987. Sediments as a source for contaminants? Hydrobiologia **149**:13–30.

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.

Schwalb AN, Morris TJ, Mandrak NE, Cottenie K. 2013. Distribution of unionid freshwater mussels depends on the distribution of host fishes on a regional scale. Diversity and Distributions **19**:446–454.

Shea CP, Peterson JT, Conroy MJ, Wisniewski JM. 2013. Evaluating the influence of land use, drought and reach isolation on the occurrence of freshwater mussel species in the lower Flint River Basin, Georgia (USA). Freshwater Biology **58**:382–395.

Sietman BE, Whitney SD, Kelner DE, Blodgett KD, Dunn HL. 2001. Post-extirpation recovery of the freshwater mussel (Bivalvia: Unionidae) fauna in the upper Illinois River. Journal of Freshwater Ecology **16**:273–281.

Sloan K, Hostler J. 2014. Utilizing Yurok traditional ecological knowledge to inform climate change priorities. Final Report. Submitted to The North Pacific Landscape Conservation Cooperative US Fish and Wildlife Service. Yurok Tribe Environmental Program, Klamath, CA.

Spooner DE, Vaughn CC. 2008. A trait-based approach to species' roles in stream ecosystems: climate change, community structure, and material cycling. Oecologia **158**:307–317.

Stanley SM. 1981. Infaunal survival: alternative functions of shell ornamentation in the Bivalvia (Mollusca). Paleobiology **7**:384–393.

Stewart IT, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western North America. Journal of Climate **18**:1136–1155.

Strayer DL, Downing JA, Haag WR, King TL, Layzer JB, Newton TJ, Nichols JS. 2004. Changing perspectives on pearly mussels, North America's most imperiled animals. BioScience **54**:429–439.

Strayer DL, Malcolm HM. 2012. Causes of recruitment failure in freshwater mussel populations in southeastern New York. Ecological Applications **22**:1780–1790.

Swain DL, Langenbrunner B, Neelin JD, Hall A. 2018. Increasing precipitation volatility in twenty-first-century California. Nature Climate Change **8**:427.

Terui A, Miyazaki Y, Yoshioka A, Kadoya T, Jopp F, Washitani I. 2014. Dispersal of larvae of *Margaritifera laevis* by its host fish. Freshwater Science **33**:112–123.

Tuttle-Raycraft S, Morris TJ, Ackerman JD. 2017. Suspended solid concentration reduces feeding in freshwater mussels. Science of The Total Environment **598**:1160–1168.

Vannote RL, Minshall GW. 1982. Fluvial processes and local lithology controlling abundance, structure, and composition of mussel beds. Proceedings of the National Academy of Sciences **79**:4103–4107.

Vaughn CC. 2018. Ecosystem services provided by freshwater mussels. Hydrobiologia **810**:15–27.

Vaughn CC, Atkinson CL, Julian JP. 2015. Drought-induced changes in flow regimes lead to long-term losses in mussel-provided ecosystem services. Ecology and Evolution **5**:1291–1305.

Vaughn CC, Hoellein TJ. 2018. Bivalve impacts in freshwater and marine ecosystems. Annual Review of Ecology, Evolution, and Systematics **49**:183–208.

Vaughn CC, Nichols SJ, Spooner DE. 2008. Community and foodweb ecology of freshwater mussels. Journal of the North American Benthological Society **27**:409–423.

Vincent WF. 2009. Effects of climate change on lakes. Pages 55–60 in G. E. Likens, editor. Encyclopedia of Inland Waters. Elsevier, Amsterdam.

Voshell JR. 2002. A guide to common freshwater invertebrates of North America. McDonald & Woodward Publishing, Newark, OH.

Wagschal A, Blevins E. 2017. Western Pearlshell Mussel Impact Assessment: Dr. Fine Bridge Replacement Project, Route 101, Del Norte County, CA. California Department of Transportation, District 1, Eureka, CA.

Williams JD, Bogan AE, Butler RS, Cummings KS, Garner JT, Harris JL, Johnson NA, Watters GT. 2017. A revised list of the freshwater mussels (Mollusca: Bivalvia: Unionida) of the United States and Canada. Freshwater Mollusk Biology and Conservation **20**:33–58.

Xerces/CTUIR. 2019. Western Freshwater Mussel Database. The Xerces Society for Invertebrate Conservation and the Confederated Tribes of the Umatilla Indian Reservation Mussel Project. Available from http://xerces.org/western-freshwater-mussels/.

Northern California Climate Adaptation Project:

Vulnerability Assessment Methods and Application

Defining Terms

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

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

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

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

Vulnerability Assessment Model

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

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

---

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

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

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

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

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

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

Vulnerability Assessment Model Elements

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

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

Sensitivity & Exposure (Applies to Species Groups and Species)

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

Sensitivity & Exposure (Applies to Species ONLY)

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

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

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

Adaptive Capacity (Applies to Habitats ONLY)

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

Adaptive Capacity (Applies to Species Groups, Species)

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

---

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.