Central Valley Landscape Conservation Project

Climate Change Vulnerability Assessment (January 2017 version)

Vernal Pool Crustaceans

Vulnerability Assessment Summary

Overall Vulnerability Score and Components:

Vulnerability Component	Score
Sensitivity	Moderate-high
Exposure	High
Adaptive Capacity	Low
Vulnerability	**Moderate-high**

Overall vulnerability of vernal pool crustaceans was scored as moderate-high. The overall score is the result of moderate sensitivity, high future exposure, and low-moderate adaptive capacity scores.

Key climate factors for vernal pool crustaceans include precipitation timing and amount, and air and water temperature. Precipitation drives pool hydroperiods, affecting crustacean composition, recruitment, and predation pressure. Temperatures influence crustacean recruitment, development rates, mortality, and distribution, as species exhibit wide differences in thermal tolerances.

A key non-climate factor is land use change. Land use changes (e.g., development, road construction, agricultural conversion) have destroyed and fragmented significant acreages of vernal pools in the Central Valley, leading to crustacean biodiversity losses. Continued land use change threatens the genetic diversity and persistence of this species group. Invasive species (e.g., bullfrogs, mosquitofish) prey on and reduce crustacean populations when introduced to ephemeral water bodies.

Key disturbance mechanisms for vernal pool crustaceans include flooding, wind, insects, and grazing. Flooding and wind facilitate crustacean dispersal, although flooding dispersal is now inhibited by water and flood control projects. Several predatory insects prey on crustaceans. Grazing may help maintain water availability in vernal pools by mediating evaporative losses to vegetation.

Vernal pool crustaceans exhibit a moderate degree of specialization; they are prey generalists, but are completely dependent on vernal pool and other ephemeral water bodies for habitat, as well as on wind, overland flow, and animals for dispersal. Key non-climate factors for vernal pool crustaceans include land use change, urban/suburban development, roads/highways/trails, and invasive and problematic species.

Vernal pool crustacean populations exhibit fragmented and isolated populations that are vulnerable to extirpation due to low landscape occupancy and dependence on external mechanisms for dispersal (e.g., flooding, wind, animal dispersal). Urban/suburban development, agricultural development, geologic features, and invasive species act as landscape barriers, affecting crustacean gene flow and dispersal.

This species group exhibits low interspecific species diversity, but highly evolved life histories and genetic exchange between generations via egg dormancy may enhance resilience. In general, this species group is more resilient to climate-related pressures than it is to human-induced habitat loss and alteration.

Management potential for vernal pool crustaceans was scored as moderate, and likely consists of regulatory support from the Endangered Species Act, preventing further habitat loss and alteration, and managing grazing to sustain water in vernal pool systems.

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Introduction

Description of Priority Natural Resource

Vernal pools contain more than 34 crustacean species (King et al. 1996), many of them endemic to California[1]. These obligate aquatic organisms have evolved to accommodate the ephemeral and highly variable hydroperiod of vernal pools in California's Mediterranean climate. Species include vernal pool fairy shrimp (*Branchinecta lynchi*), the vernal pool tadpole shrimp (*Lepidurus packardi*), California fairy shrimp (*Linderiella occidentalis*), and longhorn fairy shrimp (*Branchinecta longiantenna*).

As part of the Central Valley Landscape Conservation Project, workshop participants identified vernal pool crustaceans as a Priority Natural Resource for the Central Valley Landscape Conservation Project in a process that involved two steps: 1) gathering information about the species group's management importance as indicated by its priority in existing conservation plans and lists and, 2) a workshop with stakeholders to identify the final list of Priority Natural Resources, which includes habitats, species groups, and species.

The rationale for choosing the vernal pool crustaceans as a Priority Natural Resource included the following: the species group has high management importance, the species group's conservation needs are not entirely represented within a single priority habitat, and for the species group's high level of endemism. Please see Appendix A: "Priority Natural Resource Selection Methodology" for more information.

Vulnerability Assessment Methodology

During a two-day workshop in October of 2015, 30 experts representing 16 Central Valley resource management organizations assessed the vulnerability of priority natural resources to changes in climate and non-climate factors, and identified the likely resulting pressures, stresses, and benefits (see Appendix B: "Glossary" for terms used in this report). The expert opinions provided by these participants are referenced throughout this document with an endnote indicating its source[1]. To the extent possible, scientific literature was sought out to support expert opinion garnered at the workshop. Literature searches were conducted for factors and resulting pressures that were rated as high or moderate-high, and all pressures, stresses, and benefits identified in the workshop are included in this report. For more information about the vulnerability assessment methodology, please see Appendix C: "Vulnerability Assessment Methods and Application." Projections of climate and non-climate change for the region were researched and are summarized in Appendix D: "Overview of Projected Future Changes in the California Central Valley".

Vulnerability Assessment Details

Climate Factors

Workshop participants scored the resource's sensitivity to climate factors and this score was used to calculate overall sensitivity. Future exposure to climate factors was scored and the overall exposure score used to calculate climate change vulnerability.

Climate Factor	Sensitivity	Future Exposure
Air temperature	Moderate-high	High
Extreme events: drought	Moderate	High
Extreme events: more heat waves	-	High
Extreme events: storms	Moderate	-
Increased flooding	-	High
Precipitation (amount)	High	High
Precipitation (timing)	High	High
Timing of snowmelt/runoff	-	Moderate
Water temperature	High	High
Overall Scores	**Moderate-high**	**High**

As obligate aquatic organisms, vernal pool crustacean exposure to climate change will largely be linked with changes in aquatic habitat availability and quality (Pyke 2005). Shifts in winter precipitation and annual air temperatures are likely to affect vernal pool hydroperiods (Pyke 2004, 2005; Lawler et al. 2010).

Precipitation (amount)

> ***Sensitivity:*** *High (high confidence)*
> ***Future exposure:*** *High (high confidence)*

Although precipitation models for California are highly uncertain, some projections suggest that annual precipitation will remain quite variable over the next century, and may increase slightly in the Sacramento River Basin and decrease slightly in the San Joaquin River Basin by 2050 (Bureau of Reclamation 2015), and precipitation extremes may increase (Toreti et al. 2013).

Precipitation (timing)

> ***Sensitivity:*** *High (high confidence)*
> ***Future exposure:*** *High (high confidence)*

Shifts in precipitation volume and timing can impact the length and frequency of vernal pool inundation, influencing crustacean habitat suitability (Pyke & Marty 2005), recruitment (U.S. Fish and Wildlife Service 2003), and species composition and richness (King et al. 1996; Ripley & Simovich 2008). For example, vernal pool crustacean species richness is positively correlated with pool depth, surface area, and ponding duration (King et al. 1996; Ripley & Simovich 2008); longer pool inundation allows completion of different life stages in species with both rapid and longer development periods, while greater surface area provides spatial heterogeneity (King et al. 1996). Across the Central Valley, increasing inundation frequency and duration may increase crustacean breeding opportunities in currently marginal habitats (Pyke 2005). However, year-round inundation and/or inundation that extends beyond a few months can increase predation pressure, particularly in habitats that currently experience the longest hydroperiods (Pyke 2005). Prolonged inundation may also facilitate shifts to less favorable marsh habitat dominated by emergent vegetation (U.S. Fish and Wildlife Service 1994).

Current pool characteristics and geographical locations within the Central Valley will largely influence vernal pool response to climate-related pressures and associated crustacean stresses (Pyke 2005). For example, larger, deeper pools may show less of a response to precipitation shifts than shallow pools that currently provide marginal habitat; with shifts in precipitation, these shallow pools could experience significant increases or decreases in habitat suitability for vernal pool crustaceans (Pyke 2005). Similarly, vernal pools in the central part of the study region are likely to show the largest response to climate variability because they currently exhibit highly variable hydrology from year to year (Pyke 2005). Comparatively, vernal pools in the southern (severely water-limited) and northern (water-rich) end of the study region may show less response to climate change due to their more predictable hydroperiod (Pyke 2005). However, shifts in precipitation timing could affect ponds at the southern and northern ends of the study region if precipitation falls before or after the traditional inundation season (Pyke 2005). Additionally, precipitation shifts are also likely to interact with land use practices and habitat loss to cause variable impacts on pool hydrology and crustacean communities at the individual and landscape level (Pyke 2004; Pyke & Marty 2005).

Vernal pool crustaceans have evolved to accommodate the ephemeral and highly variable hydroperiod of vernal pools in California's Mediterranean climate. Adaptations include short development times, high reproduction rates, and dormant egg stages that can survive desiccation (U.S. Fish and Wildlife Service 2003). Many species can complete their entire life cycle during one ponding season, and several species complete multiple life cycles if ponding duration is long enough (U.S. Fish and Wildlife Service 2003). However, the succession of crustaceans over time in a given pool is sensitive to pool inundation length; precipitation changes could alter hydroperiods and therefore fragment these successions[1].

Water temperature

Sensitivity: *High (high confidence)*
Future exposure: *High (high confidence)*

Water temperature likely cues cyst hatching (Eriksen & Belk 1999), controls development rates, and influences immature and adult crustacean mortality (Helm 1998; U.S. Fish and Wildlife Service 2005). Sensitivity to temperature varies by species (U.S. Fish and Wildlife Service 2005). For example, warmer water temperatures may inhibit reproduction in cold pool-affiliated species such as the vernal pool fairy shrimp (*Branchinecta lynchi*), which requires pool temperatures of 50°F or below to successfully breed (Helm 1998; Eriksen & Belk 1999), and the vernal pool tadpole shrimp (*Lepidurus packardi*), whose hatching rates decline above 68°F (Ahl 1991). Temperatures above 75°F can also cause adult and immature vernal pool fairy shrimp mortality (Helm 1998). Comparatively, the California fairy shrimp (*Linderiella occidentalis*) appears tolerant of warm temperatures, and cold temperatures may limit the distribution of the longhorn fairy shrimp (*Branchinecta longiantenna*) to southern portions of the Central Valley (U.S. Fish and Wildlife Service 2005).

Air temperature

Sensitivity: *Moderate-high (high confidence)*
Future exposure: *High (high confidence)*

Temperature is projected to increase over the next century (Bureau of Reclamation 2015). Regardless of changes in precipitation, warmer temperatures are expected to increase evapotranspiration and cause drier conditions (Cook et al. 2015).

Vernal pool crustaceans utilize egg dormancy to survive exposure to high and cold temperatures during dry pool phases (U.S. Fish and Wildlife Service 2003). Warm air temperatures during and following rain events can negatively affect some vernal pool crustacean species' recruitment by causing increases in pond temperature, leading to immature or adult mortality (Helm 1998). If shifts in air temperature and precipitation are not in line, there could be potentially severe results for this species group (e.g., truncated wetted period)[1].

Drought

Sensitivity: *Moderate (Moderate confidence)*
Future exposure: *High (high confidence)*

Over the coming century, the frequency and severity of drought is expected to increase due to climate change (Hayhoe et al. 2004; Cook et al. 2015; Diffenbaugh et al. 2015; Williams et al. 2015), as warming temperatures exacerbate dry conditions in years with low precipitation, causing more severe droughts than have previously been observed (Cook et al. 2015; Diffenbaugh et al. 2015). Recent studies have found that anthropogenic warming has substantially increased the overall likelihood of extreme California droughts, including decadal and multi-decadal events (Cook et al. 2015; Diffenbaugh et al. 2015; Williams et al. 2015).

Timing of snowmelt & runoff

Future exposure: *Moderate (moderate confidence)*

Earlier snowmelt & runoff will alter flooding regimes and contribute to warmer water temperatures (Yarnell et al. 2010), altering vernal pool crustacean habitat suitability.

Workshop participants did not further discuss the following factors beyond assigning scores.

Storms

Sensitivity: *Moderate (moderate confidence)*

Heat waves

Sensitivity: *Moderate (moderate confidence)*
Future exposure: *High (high confidence)*

Non-Climate Factors

Workshop participants scored the resource's sensitivity and current exposure to non-climate factors, and these scores were then used to assess their impact on climate change sensitivity.

Non-Climate Factor	Sensitivity	Current Exposure
Dams, levees, & water diversions	Moderate	Low-moderate
Invasive & other problematic species	Moderate-high	High
Nutrient loading	Low-moderate	Moderate
Urban/suburban development	High	Moderate
Overall Scores	**Moderate-high**	**Moderate**

Urban/suburban development, land use change, roads/highways

Sensitivity: *High (high confidence)*
Current exposure: *Moderate (moderate confidence)*
Pattern of exposure: *Consistent across the landscape.*

Urban/suburban and agricultural development have destroyed significant portions of historical vernal pool habitat in the Central Valley and other areas of California (Holland 1998, 2009; Bartolome et al. 2014; Witham et al. 2014), contributing to local extinctions of rare and endemic vernal pool crustacean populations (King et al. 1996; King 1998). In addition to destroying habitat and causing direct vernal pool crustacean mortality, land use changes such as development and road/highway construction alter habitat quality by affecting regional hydrology (U.S. Fish and Wildlife Service 2005; Witham et al. 2014). For example, land use changes can disrupt or disconnect surface water flows across the landscape, on which vernal pools are dependent. Altered surface flows can leave downslope pools dry when they would otherwise be inundated[1], as well as fragment crustacean populations or meta-populations by removing a key dispersal mechanism (Fugate 1998; Simovich 1998).

Continued urban and infrastructure expansion threaten many vernal pool crustacean populations, particularly those residing in ditches, swales, and smaller landscape depressions; these areas are often overlooked in vernal pool inventories, and thus have no regulatory oversight (U.S. Fish and Wildlife Service 2005). Additional pool loss and fragmentation will likely further impair gene flow and reduce crustacean genetic variability by reducing gene flow "stepping stones" between pond habitats within larger complexes (Fugate 1998; Simovich 1998). Fragmentation reduces habitat quantity in its wake, and it also reduces the quality of the remaining habitat by how useful it is to various taxa that inhabit it. Additionally, isolated rangelands are difficult for livestock operations and habitat quality at fragmented sites declines. Central Valley vernal pools and vernal pool landscapes survived the last mega-drought in part because of cyst/seed adaptations; fragmentation may undermine this mechanism in the future[1].

Invasive & other problematic species

> ***Sensitivity:*** *Moderate-high (moderate confidence)*
> ***Current exposure:*** *High (moderate confidence)*
> ***Pattern of exposure:*** *Localized, where no grazing occurs.*

Vernal pool crustaceans are vulnerable to predation by several non-native species, including mosquitofish (*Gambusia affinis*) (Leyse et al. 2004) and bullfrogs (*Rana catesbeiana*) (U.S. Fish and Wildlife Service 1994). Mosquitofish have been introduced into many fishless waters in California, including vernal pools, for mosquito control (U.S. Fish and Wildlife Service 1994) and/or through flooding (Smith 2001). Bullfrogs cannot establish permanent populations in vernal pool systems because they require year-round water, but dispersing males can temporarily occupy vernal pool habitat and prey upon crustaceans during wet phases (U.S. Fish and Wildlife Service 1994). Pools featuring these and other predators exhibit lower crustacean abundance (Leyse et al. 2004), and predation risk increases with length of ponding duration (Zedler 2003).

Dams, levees, & water diversions

> ***Sensitivity:*** *Moderate (high confidence)*
> ***Current exposure:*** *Low-moderate (low confidence)*
> ***Pattern of exposure:*** *Consistent across the landscape.*

Water supply and flood control activities for agriculture and urban areas contribute to crustacean habitat loss, fragmentation, and alteration, including significant changes to pool hydroperiods. For example, water diversions can cause premature pool drydown and inhibit life cycle completion, while unseasonal water additions in summer can disrupt life cycles, heighten predation risk, and facilitate conversion to less favorable marsh habitat (U.S. Fish and Wildlife Service 1994).

Nutrient loading

Sensitivity: *Low-moderate (moderate confidence)*
Current exposure: *Moderate (moderate confidence)*
Pattern of exposure: *Consistent across the landscape.*

Disturbance Regimes

Workshop participants scored the resource's sensitivity to disturbance regimes, and these scores were used to calculate climate change sensitivity.

Overall sensitivity to disturbance regimes: *Moderate (high confidence)*

Flooding

Future exposure: *High (high confidence)*

Flooding as a result of winter and spring rains was likely one of the key historical dispersal mechanisms for vernal pool crustaceans (U.S. Fish and Wildlife Service 2003), facilitating diversity and genetic exchange between neighboring pools (Poirier 2012). However, flood control and agricultural water diversion projects now limit dispersal via this mechanism (U.S. Fish and Wildlife Service 2003), although overland flow associated with large precipitation events may still disperse some crustacean species (U.S. Fish and Wildlife Service 2005). Flooding can also introduce predatory fish and non-native species to vernal pool and other ephemeral systems, increasing crustacean predation risk (Smith 2001).

Wind

Wind dispersal of vernal pool crustaceans may occur during dry vernal pool periods (Poirier 2012). However, wind dispersal distances are small (<30 m), indicating that wind likely facilitates only within-site diversity (Vanschoenwinkel et al. 2009).

Insects

Vernal pool crustaceans are vulnerable to predatory insects, which are very common in vernal pool habitats in the study area (King et al. 1996).

Grazing

Grazing may help prolong vernal pool ponding time by reducing plant cover and associated evaporative demand (Marty 2005; Pyke & Marty 2005), enhancing vernal pool crustacean recruitment opportunities and diversity (Marty 2005).

Dependency on habitat and/or other species

Workshop participants scored the resource's dependency on habitat and/or other species, and these scores were used calculate climate change sensitivity.

Overall degree of specialization*: Moderate (high confidence)*
Dependency on one or more sensitive habitat types: *High (high confidence)*

Description of habitat: *Vernal pools within grasslands topography, presence of hardpan layer.*

Dependency on specific prey or forage species: *Low (high confidence)*

Dependency on other critical factors that influence sensitivity: *Moderate (low confidence)*

Description of other dependencies: *Dispersal vectors.*

Vernal pool species rely on ephemeral water sources; some species are vernal pool endemics, while others will also occasionally utilize swales and ditches if deposited there and if water is available (King et al. 1996). Vernal pools have segregated crustacean populations within different watersheds (King et al. 1996; U.S. Fish and Wildlife Service 2003). Dispersal vectors including overland water flow, wind, and animal-mediated dispersal are critical for genetic exchange and migration of this species group, facilitating new colonization opportunities and contributing to genetic diversity between ponds (King et al. 1996; Fugate 1998; U.S. Fish and Wildlife Service 2003, 2005).

Adaptive Capacity

Workshop participants scored the resource's adaptive capacity and the overall score was used to calculate climate change vulnerability.

Adaptive Capacity Component	Score
Extent, Integrity, & Continuity	Low
Landscape Permeability	Low
Resistance & Recovery	Low-moderate
Intraspecific Species Group Diversity	Low
Overall Score	**Low**

Extent, status, and dispersal ability

Overall degree extent, integrity, connectivity, and dispersal ability: *Low (high confidence)*

Geographic extent: *Endemic to a particular area (high confidence)*

Health and functional integrity: *Fairly degraded (high confidence)*

Population connectivity: *Isolated and/or quite fragmented (high confidence)*

Dispersal ability: *Low (high confidence)*

Vernal pool crustaceans exhibit fragmented, isolated, and specialized populations (King et al. 1996), mirroring the distributed nature and unique hydrology of vernal pool systems (U.S. Fish and Wildlife Service 2005). Many species have sporadic and low occurrences on the landscape; for example, in a survey of the Central Valley, King et al. (1996) found that over 25% of vernal pool crustacean species occurred only in a single pool, and an additional 40% of species occurred only in a single site (i.e., vernal pool complex). Low landscape occupancy makes many vernal pool crustaceans vulnerable to extirpation. For example, King (1998) estimates that historic vernal pool destruction in California has contributed to a 15-33% loss of vernal pool crustacean biodiversity since the 1800s. Several vernal pool crustaceans are now listed as threatened or endangered under the Endangered Species Act (U.S. Fish and Wildlife Service 1994), largely due to declines in habitat availability as vernal pools have been lost or altered by various forms of development (U.S. Fish and Wildlife Service 1994, 2003, 2005). Crustacean dispersal only occurs via water movement (e.g., floods), wind, and/or via animal dispersal (e.g., migratory birds; U.S. Fish and Wildlife Service 2003).

Landscape permeability

Overall landscape permeability: *Low (high confidence)*
Impact of various factors on landscape permeability:
Urban/suburban development: *High (high confidence)*
Agriculture & rangeland practice (refers to agricultural development): *High (high confidence)*
Geologic feature: *High (high confidence)*
Invasive & other problematic species: *Moderate-high (high confidence)*
Dams, levees, & water diversions: *Moderate (moderate confidence)*

Flood control projects and water diversions for urban and agricultural use have all but eliminated natural flooding and overland flow as a dispersal mechanism for vernal pool crustaceans (U.S. Fish and Wildlife Service 2003). Dispersal via migratory birds may facilitate introductions to areas otherwise isolated by geologic barriers (e.g., different watersheds; U.S. Fish and Wildlife Service 2003). However, human-related disturbance decreases vernal pool wildlife use, especially waterfowl and waterbirds, which in turn reduces transport of cysts over the long-term[1].

Resistance and recovery

Overall ability to resist and recover from stresses: *Low-moderate (high confidence)*
Resistance to stresses/maladaptive human responses: *Moderate (moderate confidence)*
Resistance to climate factors: *Moderate-high*
Resistance to non-climate factors: *Low-moderate*
Ability to recover from stresses/maladaptive human response impacts: *Low-moderate (moderate confidence)*
Recovery from climate factors: *Low-moderate*
Recovery from non-climate factors: *Low*

Vernal pool crustaceans have evolved several life history strategies that enhance resistance to variable climatic conditions, including short development times, high reproductive rates, and egg dormancy (U.S. Fish and Wildlife Service 2003). For example, dormant fairy shrimp cysts can persist in the soil for more than a decade (Belk 1998), and not all cysts hatch in a given year, forming a bank for future suitable climatic periods (U.S. Fish and Wildlife Service 2003). However, this species is not resistant to human land uses that destroy, fragment, or alter aquatic habitat availability or quality (U.S. Fish and Wildlife Service 1994, 2003, 2005).

Species group diversity

Overall species group diversity: *Low (moderate confidence)*
Diversity of life history strategies: *Low (high confidence)*
Genetic diversity: *Moderate-high (low confidence)*
Behavioral plasticity: *Low (high confidence)*
Phenotypic plasticity: *Low (moderate confidence)*

Pools may support a variety of crustaceans and pools within the same complex may feature different species assemblages (Simovich 1998). Across the landscape, species assemblages are often similar in pools with similar soil and hydroperiod characteristics (King et al. 1996). Most vernal pool crustaceans are vernal pool specialists, although some are able to utilize other aquatic habitat types (e.g., lakes, streams; King et al. 1996). There may be some life history diversity amongst vernal pool crustaceans, with some species developing and reproducing rapidly, and some species taking longer to develop (King et al. 1996). Egg dormancy is also an important life history strategy for many of these species (King et al. 1996), contributing to persistence during adverse climatic conditions and enhancing genetic diversity by causing breeding overlap between many generations (Fugate 1998). Although some studies indicate that genetic diversity in these species may be low due to limited gene flow and genetic pressures such as the founder effect (reviewed in Simovich 1998), a synthesis of genetic diversity across freshwater crustaceans in North America indicates that genetic variation within and between populations in different pools may be high (reviewed in Fugate 1998).

Management potential

Workshop participants scored the resource's management potential.

Management Potential Component	Score
Species value	Low-moderate
Societal support	Moderate
Agriculture & rangeland practices	High

Extreme events	Low
Converting retired land	Low-moderate
Managing climate change impacts	Moderate-high
Overall Score	**Moderate**

Value to people

Value to people: *Low-moderate (high confidence)*

Support for conservation

Degree of societal support for management and conservation: *Moderate (high confidence)*

Degree to which agriculture and/or rangelands can benefit/support/increase resilience: *High (high confidence)*
Description of support: *Rangelands can benefit this species group, but not agriculture.*

Degree to which extreme events (e.g., flooding, drought) influence societal support for taking action: *Low (high confidence)*

Likelihood of converting land to support species group

Likelihood of (or support for) converting retired agriculture land to maintain or enhance species group: *Moderate (high confidence)*

Likelihood of managing or alleviating climate change impacts: *Moderate-high (high confidence)*

There is some regulatory support for management of vernal pool crustaceans because several species are listed under the Endangered Species Act and have an associated recovery plan (U.S. Fish and Wildlife Service 1994, 2003, 2005). Preventing vernal pool habitat loss from human land use represents a critical management strategy for the persistence, genetic diversity, and climate resilience of this species group (U.S. Fish and Wildlife Service 1994, 1994, 2005; Belk 1998; Fugate 1998), as many crustaceans may exist in only a few pools on the landscape (King et al. 1996) and banked eggs can stimulate population increases and genetic diversity during favorable climatic periods (Belk 1998; U.S. Fish and Wildlife Service 2003). As of 2012, 30% of existing vernal pool habitat in the Central Valley was under some sort of protective land management agreement (Witham et al. 2014). Low to moderate intensity grazing may help maintain water in vernal pool systems even in a drier climate, allowing crustacean reproduction (Pyke & Marty 2005). However, stocking rates will likely require adjustment depending on precipitation and other climatic changes (Lawler et al. 2010).

Literature Cited

Ahl JSB. 1991. Factors affecting contributions of the tadpole shrimp, Lepidurus packardi, to its oversummering egg reserves. Pages 137–143 in D. Belk, H. J. Dumont, and N. Munuswamy, editors. Studies on large branchiopod biology and aquaculture. Springer Netherlands. Available from http://link.springer.com/chapter/10.1007/978-94-011-3366-1_16 (accessed April 27, 2016).

Bartolome JW, Allen-Diaz BH, Barry S, Ford LD, Hammond M, Hopkinson P, Ratcliff F, Spiegal S, White MD. 2014. Grazing for biodiversity in Californian Mediterranean grasslands. Rangelands **36**:36–43.

Belk D. 1998. Global status and trends in ephemeral pool invertebrate conservation: implications for Californian fairy shrimp. Pages 147–150 in C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren Jr., and R. Ornduff, editors. Ecology, conservation, and management of vernal pool ecosystems - proceedings from a 1996 conference. California Native Plant Society, Sacramento, CA.

Bureau of Reclamation. 2015. Sacramento and San Joaquin Basins study, report to Congress 2015. U.S. Department of the Interior, Bureau of Reclamation, Mid Pacific Region. Prepared by CH2M Hill. Available from http://www.usbr.gov/watersmart/bsp/.

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

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.

Eriksen CH, Belk D. 1999. Fairy shrimps of California's puddles, pools, and playas. Mad River Press.

Fugate M. 1998. Branchinecta of North America: population structure and its implications for conservation practice. Pages 140–146 in C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren Jr., and R. Ornduff, editors. Ecology, conservation, and management of vernal pool ecosystems – proceedings from a 1996 conference. California Native Plant Society, Sacramento, CA.

Hayhoe K et al. 2004. Emissions pathways, climate change, and impacts on California. Proceedings of the National Academy of Sciences **101**:12422–12427.

Helm BP. 1998. Biogeography of eight large branchiopods endemic to California. Pages 124–139 in C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren Jr., and R. Ornduff, editors. Ecology, conservation, and management of vernal pool ecosystems – proceedings from a 1996 conference. California Native Plant Society, Sacramento, CA.

Holland RF. 1998. Great Valley vernal pool distribution, photorevised 1996. Pages 71–75 in C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren Jr., and R. Ornduff, editors. Ecology, conservation, and management of vernal pool ecosystems – proceedings from a 1996 conference. California Native Plant Society, Sacramento, CA. Available from http://www.elkhornsloughctp.org/uploads/files/1401303246Holland.%201998.%20Great%20Valley%20vernal%20pool%20distribution,%20photorevised..pdf.

Holland RF. 2009. California's Great Valley vernal pool habitat status and loss: rephotorevised 2005. Auburn, CA. Available from http://www.vernalpools.org/vpreports/Great%20Valley%20Vernal%20Pool%20Distribution_Final.pdf.

King JL. 1998. Loss of diversity as a consequence of habitat destruction in California vernal pools. Pages 119–123 in C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren Jr., and R. Ornduff, editors. Ecology, conservation, and management of vernal pool ecosystems – proceedings from a 1996 conference. California Native Plant Society, Sacramento, CA.

King JL, Simovich MA, Brusca RC. 1996. Species richness, endemism and ecology of crustacean assemblages in northern California vernal pools. Hydrobiologia **328**:85–116.

Lawler JJ et al. 2010. Resource management in a changing and uncertain climate. Frontiers in Ecology and the Environment **8**:35–43.

Leyse KE, Lawler SP, Strange T. 2004. Effects of an alien fish, Gambusia affinis, on an endemic California fairy shrimp, Linderiella occidentalis: implications for conservation of diversity in fishless waters. Biological Conservation **118**:57–65.

Marty JT. 2005. Effects of cattle grazing on diversity in ephemeral wetlands. Conservation Biology **19**:1626–1632.

Poirier PA. 2012. Physical and chemical correlates of Sacramento County vernal pool crustaceans. Master of Science. University of the Pacific, Stockton, CA. Available from http://www.vernalpools.org/documents/Thesis_Poirier.pdf.

Pyke CR. 2004. Habitat loss confounds climate change impacts. Frontiers in Ecology and the Environment **2**:178–182.

Pyke CR. 2005. Assessing climate change impacts on vernal pool ecosystems and endemic branchiopods. Ecosystems **8**:95–105.

Pyke CR, Marty J. 2005. Cattle grazing mediates climate change impacts on ephemeral wetlands. Conservation Biology **19**:1619–1625.

Ripley BJ, Simovich MA. 2008. Species richness on islands in time: variation in ephemeral pond crustacean communities in relation to habitat duration and size. Hydrobiologia **617**:181–196.

Simovich MA. 1998. Crustacean biodiversity and endemism in California's ephemeral wetlands. Pages 107–118 in C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren Jr., and R. Ornduff, editors. Ecology, conservation, and management of vernal pool ecosystems – proceedings from a 1996 conference. California Native Plant Society, Sacramento, CA.

Smith DG. 2001. Pennak's freshwater invertebrates of the United States: Porifera to Crustacea. John Wiley & Sons.

Toreti A, Naveau P, Zampieri M, Schindler A, Scoccimarro E, Xoplaki E, Dijkstra HA, Gualdi S, Luterbacher J. 2013. Projections of global changes in precipitation extremes from Coupled Model Intercomparison Project Phase 5 models. Geophysical Research Letters **40**:4887–4892.

U.S. Fish and Wildlife Service. 1994. Endangered and threatened wildlife and plants; determination of endangered status for the Conservancy fairy shrimp, longhorn fairy shrimp, and the vernal pool tadpole shrimp; and threatened status for the vernal pool fairy shrimp. Federal Register **59**:48136–48153.

U.S. Fish and Wildlife Service. 2003. Endangered and Threatened wildlife and plants; Final designation of critical habitat for four vernal pool crustaceans and eleven vernal pool plants in California and southern Oregon: Final Rule. Federal Register **68**:46684–46762.

U.S. Fish and Wildlife Service. 2005. Recovery plan for vernal pool ecosystems of California and southern Oregon. U.S. Fish and Wildlife Service, Region 1, Portland, OR. Available from http://www.fws.gov/sacramento/ES/Recovery-Planning/Vernal-Pool/es_recovery_vernal-pool-recovery.htm.

Vanschoenwinkel B, Gielen S, Seaman M, Brendonck L. 2009. Wind mediated dispersal of freshwater invertebrates in a rock pool metacommunity: differences in dispersal capacities and modes. Hydrobiologia **635**:363–372.

Williams AP, Seager R, Abatzoglou JT, Cook BI, Smerdon JE, Cook ER. 2015. Contribution of anthropogenic warming to California drought during 2012-2014. Geophysical Research Letters **in press**:1–10.

Witham CW, Holland RF, Vollmar JE. 2014. Changes in the distribution of Great Valley vernal pool habitats from 2005 to 2012. Available from http://www.vernalpools.org/2012CVPIA/20141914_Final_2012_Remapping_Report.pdf.

Yarnell SM, Viers JH, Mount JF. 2010. Ecology and management of the spring snowmelt recession. BioScience **60**:114–127.

Zedler PH. 2003. Vernal pools and the concept of "isolated wetlands." Wetlands **23**:597–607.

[1] Expert opinion, Central Valley Landscape Conservation Project Vulnerability Assessment Workshop, Oct. 8-9, 2015.