Central Valley Landscape Conservation Project

Climate Change Vulnerability Assessment (January 2017 version)

Grasslands

Vulnerability Assessment Summary

Overall Vulnerability Score and Components:

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

Overall vulnerability of the grasslands habitat was scored as moderate-high. The score is the result of high sensitivity, high future exposure, and moderate adaptive capacity scores.

Key climate factors for grassland systems include soil moisture, precipitation timing and amount, drought, and air temperature. These factors influence germination, species composition and diversity, productivity, and phenology.

Key disturbance mechanisms include grazing, wildfire, and insects; all of these factors influence invasive species pressure, species composition, and grassland biomass.

Key non-climate factors include urban/suburban development, agricultural and rangeland practices, land use change, nutrient loading, invasive and problematic species, and roads, highways, and trails. These stressors fragment and destroy habitat, alter species composition, and typically increase vulnerability to invasion. Exotic annual species have significantly altered the structure and function of California grasslands.

Grasslands represent a significant portion of Central Valley surface area, but have experienced varying levels of habitat fragmentation and alteration, primarily from agricultural and urban development and exotic species establishment and dominance. Many of the non-climate stressors listed above, in addition to energy production and mining, act as landscape barriers. Although grassland habitats have been extensively altered, they still support high floristic and wildlife diversity.

Resilience varies amongst component species; wildflowers have demonstrated diversity losses in response to warmer and drier conditions. In general, annual species resilience is fostered by persistent seedbanks, while perennial species resilience is tied with deeper rooting systems, which facilitate tolerance of short-term precipitation fluctuations. However, native dispersal may be limited and natural recovery of invaded or altered systems is difficult, limiting migration and recovery potential in response to climate stressors and habitat fragmentation.

Management potential for grassland habitats was scored as moderate and is likely influenced by agricultural area restoration efforts, invasive species control, and rangeland management practices.

Table of Contents

Introduction

Description of Priority Natural Resource

Central Valley grasslands are open grasslands that support a diversity of annual and perennial plant species. These grasslands are characterized by winter precipitation and seasonal summer drought, and exhibit high temporal and spatial diversity (Lulow & Young 2011a; Bartolome et al. 2014; Spiegal et al. 2014).

As part of the Central Valley Landscape Conservation Project, workshop participants identified the grasslands habitat as a Priority Natural Resource for the Central Valley Landscape Conservation Project in a process that involved two steps: 1) gathering information about the habitat'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 grasslands habitat as a Priority Natural Resource included the following: the habitat has high management importance. 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	High
Increased wildfire	-	High
Precipitation (amount)	High	Moderate
Precipitation (timing)	Moderate-high	High
Soil moisture	High	-
Overall Scores	**High**	**High**

Modeling by Gardali et al. (2011) indicates that grassland habitat in the Sacramento Valley may decline 1-20% by 2070 due to warmer winter temperatures and variable precipitation, leading to overall drier conditions. Modeling for the San Joaquin Valley indicates similar trends, with a 6-11% loss of grassland habitat by 2070 (PRBO Conservation Science 2011). A more recent assessment looking at both warmer/wetter and warmer/drier conditions under high and low emissions scenarios project that 52-84% of current grassland habitat in California will remain climatically suitable by the end of the century (2070-2099). The eastern edge of the Central Valley, particularly in the southern portion of the study region, is projected to become climatically unsuitable under drier conditions, while under wetter conditions, large portions of the northern Central Valley may become unsuitable (Thorne et al. 2016).

Soil moisture

Sensitivity: *High (high confidence)*

Between 1951-1980, climatic water deficit increased by 2 mm in the Central Valley, compared to an average of 17 mm statewide (Thorne et al. 2015). Thorne et al. (2015) project that climatic water deficit is expected to increase by 131 mm in the Central Valley (compared to 140 mm statewide) by 2070-2099 under a drier scenario and 44 mm (compared to 61 mm statewide) under a wetter scenario.

Soil moisture influences grassland distribution and species composition (Reever Morghan et al. 2007). Perennial grassland species are typically affiliated with more mesic areas than annual species (Bartolome et al. 2014). Higher soil moisture could facilitate oak woodland encroachment (Gordon & Rice 2000). Soil moisture – influenced by precipitation, evaporation, soil texture and depth, and plant community characteristics – typically peaks in early winter and declines throughout the growing season as evapotranspiration increases (Reever Morgan et al. 2007).

Precipitation (amount)

> ***Sensitivity:*** *High (high confidence)*
> ***Future exposure:*** *Moderate (moderate confidence)*
> ***Potential refugia:*** *Areas with deep soil.*

Although the Central Valley lies in the rain shadow of the Coast Range, a precipitation gradient exists along north-south and coastal-inland axes in the study region, with northern and coastal areas experiencing higher rainfall (Reever Morghan et al. 2007; Spiegal et al. 2014). In general, California experiences high inter-annual variability in precipitation volume, with highest rainfall occurring during El Niño-Southern Oscillation (ENSO) events (Reever Morghan et al. 2007).

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)

High precipitation variability drives variability in grassland species composition, abundance, and productivity (Hamilton et al. 1999; Jackson & Bartolome 2002; Dukes et al. 2005; Dukes & Shaw 2007; Chou et al. 2008). Higher precipitation is correlated with enhanced native plant diversity, but also with increased productivity and growth of exotic annual grasses (Chou et al. 2008; Buck-Diaz et al. 2011). High and low amounts of precipitation may also contribute to vegetative type conversion to other habitat types[1].

Precipitation (timing)

> ***Sensitivity:*** Moderate-*high (high confidence)*
> ***Future exposure:*** *High (high confidence)*
> ***Potential refugia:*** *North-facing slopes, possibly shrubs and streams that provide moisture.*

The majority of rainfall in the study region occurs from October-April. Shifts in seasonal rain delivery, particularly in fall and spring, influences grassland composition (Reever Morghan et al. 2007; Eviner 2014) and diversity (Harrison et al. 2015). For example, lower winter precipitation following germinating rains may favor perennials and forbs over annual grass species (Hamilton et al. 1999), while consistent rain favors annual establishment and dominance (Eviner 2014; Spiegal et al. 2014). Altered precipitation timing may also facilitate establishment of new exotics and/or increase cover of problematic invasive species. For example, increasing late spring moisture may increase the abundance and productivity of non-native annuals that thrive through late summer, including medusahead (*Elymus caput-medusae*) and barbed goat grass (*Aegilops triuncialis*), and non-native forbs like yellow starthistle (*Centaurea solstitialis*)

(Eskelinen & Harrison 2014; Eviner 2014). Late spring moisture has variable impacts on native vegetation, ranging from increased production of late-season species (e.g., tarweed [*Centromadia* spp.]; Eviner 2014) to negatively affecting other native plant emergence[1]. Longer wet seasons and/or a later start to the wet season may also affect soil respiration, contributing to carbon loss in annual grasslands (Chou et al. 2008).

Drought

> ***Sensitivity:*** Moderate-*high (high confidence)*
> ***Future exposure:*** *High (high confidence)*
> ***Potential refugia:*** *No refugia identified by workshop participants.*

Compared to the preceding century (1896-1994), drought years in California have occurred twice as often in the last 20 years (1995-2014; Diffenbaugh et al. 2015). Additionally, the recent drought (2012-2014) has been the most severe drought on record in the Central Valley (Williams et al. 2015), with record accumulated moisture deficits driven by high temperatures and reduced, but not unprecedented, precipitation (Griffin & Anchukaitis 2014; Williams et al. 2015). 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).

Severe or successive drought years can alter grassland productivity and composition. For example, the recent drought has been correlated with declines in wildflower diversity, with losses concentrated amongst species with low drought tolerance (Harrison et al. 2015). Perennial grasses and forbs may be more resilient to short-term drought than annual species due to more robust root systems. Overall, grassland species are largely adapted to seasonal summer drought characteristic of Mediterranean climates, but all grassland components are vulnerable to prolonged or severe drought (Reever Morghan et al. 2007).

Air temperature

> ***Sensitivity:*** Moderate-*high (high confidence)*
> ***Future exposure:*** *High (high confidence)*
> ***Potential refugia:*** *North-facing slopes, possibly shrubs and streams that provide moisture.*

Regardless of changes in precipitation, warmer temperatures are expected to increase evapotranspiration and cause drier conditions (Cook et al. 2015).

Air temperature, including both high and low temperatures, influences grassland phenology, productivity, germination, and composition (Dukes & Shaw 2007). Annual grassland senescence timing and perennial grass summer dormancy are influenced by temperature rather than precipitation (Laude 1953; Zavaleta et al. 2003b; Cleland et al. 2006). Earlier senescence timing, which reduces plant transpiration, can alter available soil moisture in late spring and summer and drive community shifts (Zavaleta et al. 2003b). Low temperatures have been associated with declines in germination of some annual grass species (Reynolds et al. 2001), while warm spring temperatures typically increase annual grass growth rates and will likely favor increased exotic dominance in the future (Sandel & Dangremond 2012).

Air temperature also interacts with precipitation to affect grassland community composition (Dukes & Shaw 2007). For example, rains occurring during warmer periods (e.g., fall) typically correlate with higher annual dominance, while rains occurring during cooler periods (e.g., November, December) typically favor perennial species (Reever Morghan et al. 2007; Eviner 2014). Higher temperatures have also contributed to regional drought conditions and increased climatic water deficit by enhancing evaporation (Griffin & Anchukaitis 2014; Williams et al. 2015); Central Valley evaporation rates are higher than in grasslands elsewhere in the state (Major 1988).

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
Agriculture & rangeland practices	High	Moderate-high
Groundwater overdraft	Moderate-high	Moderate-high
Invasive & other problematic species	High	High
Land use change	High	High
Nutrient loading	Moderate-high	Moderate-high
Roads, highways, & trails	Moderate-high	Moderate
Urban/suburban development	High	High
Overall Scores	**High**	**Moderate-high**

Urban/suburban development

> ***Sensitivity:*** *High (high confidence)*
> ***Current exposure:*** *High (high confidence)*
> ***Pattern of exposure:*** *Consistent across the landscape, but highest around urban areas.*

Urban/suburban development destroys and fragments grassland habitat, and has contributed to significant grassland habitat loss in the Central Valley (Huenneke 1989).

Invasive & other problematic species

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

Exotic annual species have invaded and are dominant in many Central Valley grassland systems. Common invaders include yellow starthistle, medusahead, artichoke thistle (*Cynara cardunculus*), Scotch thistle (*Onopordum acanthium*), barb goat grass (*Aegilops triuncialis*), *Bromus* species, *Avena* species, *Hordeum murinum*, *Hordeum marinum*, *Lolium multiflorum*, *Brachypodium distachyon*, and *Vulpia myuros* (DiTomaso et al. 2007; Buck-Diaz et al. 2011). Invasive annual grasses can reduce native plant germination and growth and undermine wildlife habitat suitability by increasing biomass and causing higher thatch depth. Invasive species also alter ecosystem hydrology and fire regimes, and compete with native vegetation for soil moisture, light, and nutrients, contributing to reduced native biodiversity (DiTomaso et al. 2007). Mature stands of perennial bunchgrasses with high biomass may be able to resist invasion, although resistance is influenced by time and species present (Lulow 2006).

Land use change

Sensitivity: *High (high confidence)*
Current exposure: *High (high confidence)*
Pattern of exposure: *Localized around energy development.*

Land use change alters grassland extent (Huenneke 1989), exposure to invasive species (Stromberg et al. 2007), and/or the magnitude of climate change. For example, past expansion of irrigated land may have mitigated maximum summer temperatures in the Central Valley through the irrigated cooling effect, but potential future losses of irrigated land due to reduced water supply and/or increased development could exacerbate warming trends in the region (Kueppers et al. 2007).

Agricultural & rangeland practices

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

Agricultural practices can alter grassland nutrient, soil microbe, and plant community dynamics through novel or repeated disturbance (e.g., tilling, deep disking; Seabloom et al. 2003; Stromberg et al. 2007) and enhanced inputs (e.g., herbicide, fertilizer, irrigation; Steenwerth et al. 2002). These alterations can reduce native cover and increase exotic establishment and dominance, with impacts persisting for 70 or more years after cessation of agricultural activity (Steenwerth et al. 2002; Stromberg et al. 2007). For information on grazing, please see disturbance regime section.

Nutrient loading

Sensitivity: *Moderate-high (high confidence)*
Current exposure: *Moderate-high (high confidence)*

Pattern of exposure: *Consistent across the landscape.*

Nitrogen deposition can alter grassland productivity and composition, typically by increasing production and dominance of non-native annual grasses over native forbs, leading to biodiversity losses (Zavaleta et al. 2003a). When combined with shifts in spring precipitation, higher nitrogen levels may facilitate new invasions and/or expansion of late summer annuals (Eskelinen & Harrison 2014). Agricultural inputs also increase nutrient loading in regional grasslands[1].

Roads, highways, & trails

Sensitivity: *Moderate-high (high confidence)*
Current exposure: *Moderate (high confidence)*
Pattern of exposure: *Fairly consistent across the landscape.*

Road construction destroys and fragments grassland habitat. Additionally, roads, highways and trails contribute to the introduction and spread of invasive species. Maintenance activities also act as a disturbance mechanism, providing invasive colonization opportunities (Stromberg et al. 2007).

Groundwater overdraft

Workshop participants did not further discuss this factor beyond assigning a sensitivity and exposure score.

Sensitivity: *Low-moderate (high confidence)*
Current exposure: *Moderate-high (high confidence)*
Pattern of exposure: *Localized around the Tulare basin.*

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: *High (high confidence)*

Wildfire

Future exposure: *High (high confidence)*
Potential refugia: *No refugia identified by workshop participants.*

Large fire occurrence and total area burned in California are projected to continue increasing over the next century with total area burned projected to increase by up to 74% by 2085 (Westerling et al. 2011). Increased fire frequency is projected to increase grassland extent throughout California by preventing shrub encroachment and facilitating forest conversion to grassland systems (Lenihan et al. 2008).

Fire is a common disturbance regime in grassland systems, and most grassland species are fire-tolerant (D'Antonio et al. 2002). Wildfire can alter grassland species composition and exotic species dominance, but impacts are highly variable depending on timing, intensity, burn frequency, species present at time of burn, and precipitation and grazing post-burn (D'Antonio et al. 2002; Keeley et al. 2011). Shifts in fine fuel load – tied with altered precipitation regimes – may alter wildfire intensity (Keeley et al. 2011). Fire suppression is a more harmful disturbance than fire itself because of soil disturbance[1].

Insects

Insect outbreaks (i.e., grasshoppers) can lead to large losses of above-ground grassland biomass and may contribute to higher annual dominance, as grasshopper activity aligns more completely with perennial growth stages than with annual plant life histories. Phenological shifts of either grassland components and/or grasshoppers as a result of climate change could dramatically change insect herbivory pressure and relative abundance, productivity, and dominance of different grassland functional groups (Joern 1989; Schiffman 2007). Grasshopper outbreaks have been weakly correlated with hot, dry conditions (Joern 1989).

Grazing

Grazing may help decrease litter depth associated with exotic species, reducing competitive interactions with native species (Bartolome et al. 2014). However, grazing impacts depend on a variety of factors, including species present, animal used, grazing timing and intensity, and precipitation (DiTomaso et al. 2007; Stahlheber & D'Antonio 2013). A meta-analysis of grazing in California grasslands found that wet season grazing generally improves native forb and grass cover while decreasing exotic grass cover, particularly in interior grasslands; however, grazing practices need to be tailored to each site in order to mitigate increases in exotic forb cover (Stahlheber & D'Antonio 2013).

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	Moderate
Landscape Permeability	Low
Resistance & Recovery	Moderate-high
Habitat Diversity	Moderate-high
Overall Score	**Moderate**

Extent, integrity, and continuity

Overall degree of habitat extent, integrity, and continuity: *Moderate (high confidence)*
Geographic extent of habitat: *Transcontinental (high confidence)*
Structural and functional integrity of habitat: *Fairly degraded (high confidence)*
Continuity of habitat: *Patches with connectivity between them (high confidence)*

Central Valley grasslands represent close to half of the grassland habitat found in California, and make up a significant portion of the surface area within the Central Valley (Huenneke 1989). However, Central Valley grassland habitats exist in varying conditions of fragmentation and alteration. Most feature some level of exotic grass invasion (Stromberg et al. 2007), and habitat loss and fragmentation by development and agriculture is prevalent (Huenneke 1989). However, native-dominated patches are still common at smaller spatial scales (Stromberg et al. 2007). Private ranches and conservation easements may help preserve grassland habitat area and continuity by maintaining large swaths of contiguous open space (Bartolome et al. 2014).

Landscape permeability

Overall landscape permeability: *Low-moderate (high confidence)*
Impact of various factors on landscape permeability:
- ***Urban/suburban development:*** *High (high confidence)*
- ***Land use change:*** *High (high confidence)*
- ***Agricultural & rangeland practices:*** *High (high confidence)*
- ***Energy production & mining:*** *Moderate-high (high confidence)*

Roads, highways, & trails: *Moderate (high confidence)*
Invasive & other problematic species: *Moderate (high confidence)*

Agriculture, human land use, and urban development fragment grassland habitats (Huenneke 1989), with implications for species dispersal and migration.

Resistance and recovery

Overall ability to resist and recover from stressors: *Moderate-high (high confidence)*
Resistance to stressors/maladaptive human responses: *Moderate (high confidence)*
Ability to recover from stressor/maladaptive human response impacts: *Moderate-high (high confidence)*

Many annual species have abundant and long-lived seedbanks, allowing them to tolerate climatically unsuitable periods (Bartolome et al. 2014) and capitalize on periods of disturbance and low competition (Eviner 2014). However, seedlings are vulnerable to within-year weather fluctuations and water availability (Reever Morghan et al. 2007). Comparatively, perennial species may be more resilient to short-term climatic water deficits due to deeper rooting systems (Eviner 2014), but cannot respond as quickly to changing environmental conditions. Many native species appear to have limited dispersal (Schiffman 2007). Natural grassland recovery following agricultural use and exotic invasion is slow and limited (Stromberg et al. 2007).

Habitat diversity

Overall habitat diversity: *High (high confidence)*
Physical and topographical diversity of the habitat: *High (high confidence)*
Diversity of component species within the habitat: *Moderate-high (high confidence)*
Diversity of functional groups within the habitat: *Moderate-high (high confidence)*

Component species or functional groups particularly sensitive to climate change:

- Native pollinators
- Wildflowers

Keystone or foundational species within the habitat:

- Ground squirrels
- Kangaroo rats
- Cattle

Other critical factors that may affect habitat diversity:

- Soil type diversity

Central Valley grasslands support high floristic diversity, and provide critical habitat for a variety of wildlife, including many threatened and endangered species. Although these grasslands are frequently dominated by high non-native annual cover, they still support a diversity of native annual and perennial species at low abundances (Lulow & Young 2011b; Bartolome et al. 2014; Spiegal et al. 2014; California Department of Fish and Game 2016). Soil type also influences grassland diversity and species composition; for example, serpentine soils may provide some refugia for native species from exotic pressure (Harrison et al. 2003).

Native wildflower diversity appears to be particularly threatened by warmer and drier climate conditions; lower plant diversity can have cascading impacts on pollinator and wildlife populations (Harrison et al. 2015). Additionally, warmer air temperatures may also cause phenological mismatches between pollinators and their plant hosts (Memmott et al. 2007).

Management potential

Workshop participants scored the resource's management potential.

Management Potential Component	Score
Habitat value	Moderate
Societal support	Low-moderate
Agriculture & rangeland practices	High
Extreme events	Moderate
Converting retired land	Low-moderate
Managing climate change impacts	Moderate
Overall Score	**Moderate**

Value to people

Value of habitat to people: *Moderate (high confidence)*

Support for conservation

Degree of societal support for managing and conserving habitat: *Low-moderate (high confidence)*

Degree to which agriculture and/or rangelands can benefit/support/increase the resilience of this habitat: *High for rangelands only (high confidence)*
Description of support: *Rangeland grazing can be beneficial and controlled.*

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

Likelihood of converting land to habitat

Likelihood of (or support for) converting retired agriculture land to habitat: *Low-moderate (moderate confidence)*

Likelihood of managing or alleviating climate change impacts on habitat: *Moderate (moderate confidence)*

Grazing can be managed to achieve various objectives in grassland systems (Stahlheber & D'Antonio 2013). Restoring grasslands in previous agricultural lands is possible but may be difficult due to high exotic presence, variable use history (Seabloom et al. 2003; Lulow 2006; Stromberg et al. 2007), and slow soil recovery following cultivation (Steenwerth et al. 2002), although some native grasses are successful at establishing on degraded soils (Stromberg et al. 2007). Irrigation mimicking natural rainfall patterns may facilitate grassland restoration efforts (Stromberg et al. 2007), provided water supplies are available.

Literature Cited

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.

Buck-Diaz J, Harbert B, Evens J. 2011. California rangeland monitoring and mapping: a focus on grassland habitats of the San Joaquin Valley and Carrizo Plain. California Native Plant Society, Sacramento, CA. Available from http://www.cnps.org/cnps/vegetation/pdf/grassland_nrcs_report.pdf.

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/.

California Department of Fish and Game. 2016. California Wildlife Habitat Relationships System: annual grassland. Available from https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=67384&inline=1 (accessed March 1, 2016).

Chou WW, Silver WL, Jackson RD, Thompson AW, ALLEN-DIAZ B. 2008. The sensitivity of annual grassland carbon cycling to the quantity and timing of rainfall. Global Change Biology **14**:1382–1394.

Cleland EE, Chiariello NR, Loarie SR, Mooney HA, Field CB. 2006. Diverse responses of phenology to global changes in a grassland ecosystem. Proceedings of the National Academy of Sciences **103**:13740–13744.

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

D'Antonio C, Bainbridge S, Kennedy C, Bartolome J, Reynolds S. 2002. Ecology and restoration of California grasslands with special emphasis on the influence of fire and grazing on native grassland species. A report to the Packard Foundation. University of California, Berkeley. Department of Integrated Biology and Department of Environmental Science, Policy and Management, Berkeley, CA. Available from http://globalrestorationnetwork.org/uploads/files/LiteratureAttachments/120_ecology-and-restoration-of-california-grasslands-with-special-emphasis-on-the-influence-of-fire-and-grazing-on-native-grassland-species.pdf.

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.

DiTomaso JM, Enloe SF, Pitcairn MJ. 2007. Exotic plant management in California annual grasslands. Pages 281–296 in M. R. Stromberg, J. D. Corbin, and C. M. D'Antonio, editors. California grasslands: ecology and management. University of California Press, Berkeley and Los Angeles, CA. Available from http://sfc.smallfarmcentral.com/dynamic_content/uploadfiles/152/DiTomaso%20Ch22%20Stromberg.pdf.

Dukes JS, Chiariello NR, Cleland EE, Moore LA, Shaw MR, Thayer S, Tobeck T, Mooney HA, Field CB. 2005. Responses of grassland production to single and multiple global environmental changes. PLoS Biology **3**:e319.

Dukes JS, Shaw MR. 2007. Responses to changing atmosphere and climate. Pages 218–232 in M. R. Stromberg, J. D. Corbin, and C. M. D'Antonio, editors. California grasslands: ecology and management. University of California Press, Berkeley and Los Angeles, CA. Available from http://globalecology.stanford.edu/DGE/Dukes/Dukes&Shaw2007.pdf.

Eskelinen A, Harrison S. 2014. Exotic plant invasions under enhanced rainfall are constrained by soil nutrients and competition. Ecology **95**:682–692.

Eviner V. 2014. Effects of weather variation on species composition and production in California's grasslands. Grasslands, Fall 2014:1–7.

Gordon DR, Rice KJ. 2000. Competitive suppression of Quercus douglasii (Fagaceae) seedling emergence and growth. American Journal of Botany **87**:986–994.

Griffin D, Anchukaitis KJ. 2014. How unusual is the 2012–2014 California drought? Geophysical Research Letters **41**:9017–9023.

Hamilton JG, Holzapfel C, Mahall BE. 1999. Coexistence and interference between a native perennial grass and non-native annual grasses in California. Oecologia **121**:518–526.

Harrison S, Inouye BD, Safford HD. 2003. Ecological heterogeneity in the effects of grazing and fire on grassland diversity. Conservation Biology **17**:837–845.

Harrison SP, Gornish ES, Copeland S. 2015. Climate-driven diversity loss in a grassland community. Proceedings of the National Academy of Sciences of the United States of America **112**:8672–8677.

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

Huenneke LF. 1989. Distribution and regional patterns of Californian grasslands. Pages 1–12 in L. F. Huenneke and H. A. Mooney, editors. Grassland structure and function. Springer Netherlands. Available from http://link.springer.com/chapter/10.1007/978-94-009-3113-8_1 (accessed March 1, 2016).

Jackson RD, Bartolome JW. 2002. A state-transition approach to understanding nonequilibrium plant community dynamics in Californian grasslands. Plant Ecology **162**:49–65.

Joern A. 1989. Insect herbivory in the transition to California annual grasslands: did grasshoppers deliver the coup de grass? Pages 117–134 in L. F. Huenneke and H. A. Mooney, editors. Grassland structure and function. Springer Netherlands. Available from http://link.springer.com/chapter/10.1007/978-94-009-3113-8_11 (accessed February 22, 2016).

Keeley JE, Franklin J, D’Antonio C. 2011. Fire and invasive plants on California landscapes. Pages 193–221 in D. McKenzie, C. Miller, and D. A. Falk, editors. The landscape ecology of fire. Springer.

Kueppers LM, Snyder MA, Sloan LC. 2007. Irrigation cooling effect: regional climate forcing by land-use change. Geophysical Research Letters **34**:L03703.

Laude HM. 1953. The nature of summer dormancy in perennial grasses. Botanical Gazette:284–292.

Lenihan JM, Bachelet D, Neilson RP, Drapek R. 2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. Climatic Change **87**:215–230.

Lulow ME. 2006. Invasion by non-native annual Grasses: the Importance of species biomass, composition, and time among California native grasses of the Central Valley. Restoration Ecology **14**:616–626.

Lulow ME, Young TP. 2011a. Is there still native diversity in California grasslands? Fremontia **39**:6–11.

Lulow ME, Young TP. 2011b. Is there still native diversity in California grasslands? Fremontia **39**:6–11.

Major J. 1988. California climate in relation to vegetation. Pages 11–74 in M. G. Barbour and J. Major, editors. Terrestrial vegetation of California. Wiley Interscience, New York, NY.

Memmott J, Craze PG, Waser NM, Price MV. 2007. Global warming and the disruption of plant–pollinator interactions. Ecology Letters **10**:710–717.

PRBO Conservation Science. 2011. Projected effects of climate change in California: Ecoregional summaries emphasizing consequences for wildlife. Version 1.0. PRBO Conservation Science, Petaluma, CA. Available from http://data.prbo.org/apps/bssc/climatechange.

Reever Morgan K, Corbin J, Gerlach J. 2007. Water Relations. Pages 85–97 in M. R. Stromberg, J. D. Corbin, and D. C.M., editors. California Grasslands: Ecology and Management. University of California Press, Berkley, CA.

Reever Morghan KJ, Corbin JD, Gerlach J. 2007. Water relations. Pages 87–93 in M. R. Stromberg, J. D. Corbin, and C. M. D’Antonio, editors. California grasslands: ecology and management. University of California Press, Berkeley and Los Angeles, CA.

Reynolds SA, Corbin JD, D’Antonio CM. 2001. The effects of litter and temperature on the germination of native and exotic grasses in a coastal California grassland. Madroño **48**:230–235.

Sandel B, Dangremond EM. 2012. Climate change and the invasion of California by grasses. Global Change Biology **18**:277–289.

Schiffman PM. 2007. Ecology of native animals in California grasslands. Pages 180–190 in M. R. Stromberg, J. D. Corbin, and C. M. D’Antonio, editors. California grasslands: ecology and management. University of California Press, Berkeley and Los Angeles, CA. Available from http://www.csun.edu/sites/default/files/Chapt15_GrasslandBook_0.pdf.

Seabloom EW, Harpole WS, Reichman OJ, Tilman D. 2003. Invasion, competitive dominance, and resource use by exotic and native California grassland species. Proceedings of the National Academy of Sciences **100**:13384–13389.

Spiegal S, Larios L, Bartolome JW, Suding KN. 2014. Restoration management for spatially and temporally complex Californian grassland. Pages 69–104 Grassland biodiversity and conservation in a changing world. University of California Berkeley. Available from https://escholarship.org/uc/item/6dr430wn.

Stahlheber KA, D’Antonio CM. 2013. Using livestock to manage plant composition: a meta-analysis of grazing in California Mediterranean grasslands. Biological Conservation **157**:300–308.

Steenwerth KL, Jackson LE, Calderón FJ, Stromberg MR, Scow KM. 2002. Soil microbial community composition and land use history in cultivated and grassland ecosystems of coastal California. Soil Biology and Biochemistry **34**:1599–1611.

Stromberg MR, D'Antonio CM, Young TP, Wirka J, Kephart PR. 2007. California grassland restoration. Pages 254–280 in M. R. Stromberg, J. D. Corbin, and C. M. D'Antonio, editors. California grasslands: ecology and management. University of California Press, Berkeley and Los Angeles, CA. Available from http://tpyoung.ucdavis.edu/publications/2007Stromberg.pdf.

Thorne JH, Boynton RM, Flint LE, Flint AL. 2015. The magnitude and spatial patterns of historical and future hydrologic change in California' s watersheds. Ecosphere **6**:1–30.

Thorne JH, Boynton RM, Holguin AJ, Stewart JAE, Bjorkman J. 2016. A climate change vulnerability assessment of California's terrestrial vegetation. California Department of Fish and Wildlife (CDFW), Sacramento, CA. Available from https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=116208&inline.

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.

Westerling AL, Bryant BP, Preisler HK, Holmes TP, Hidalgo HG, Das T, Shrestha SR. 2011. Climate change and growth scenarios for California wildfire. Climatic Change **109**:445–463.

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.

Zavaleta ES, Shaw MR, Chiariello NR, Thomas BD, Cleland EE, Field CB, Mooney HA. 2003a. Grassland responses to three years of elevated temperature, CO2, precipitation, and N deposition. Ecological Monographs **73**:585–604.

Zavaleta ES, Thomas BD, Chiariello NR, Asner GP, Shaw MR, Field CB. 2003b. Plants reverse warming effect on ecosystem water balance. Proceedings of the National Academy of Sciences **100**:9892–9893.

[1] Expert opinion, Central Valley Landscape Conservation Project Vulnerability Assessment