Focal Resource: WET MEADOWS

CWHR Types:[1] **WTM-** Sedge species (*Carex spp*.), rush species (*Juncus spp*.), tufted hairgrass (*Deschampsia cespitosa*)

General Overview of Process

EcoAdapt, in collaboration with the U.S. Forest Service and California Landscape Conservation Cooperative (CA LCC), convened a 2.5-day workshop entitled *A Vulnerability Assessment Workshop for Focal Resources of the Sierra Nevada* on March 5-7, 2013 in Sacramento, California. Over 30 participants representing federal and state agencies, non-governmental organizations, universities, and others participated in the workshop[2]. The following document represents the vulnerability assessment results for the **WET MEADOWS ECOSYSTEM**, which is comprised of evaluations and comments from a participant breakout group during this workshop, peer-review comments following the workshop from at least one additional expert in the subject area, and relevant references from the literature. The aim of this synthesis is to expand understanding of resource vulnerability to changing climate conditions, and to provide a basis for developing appropriate adaptation responses. The resulting document is an initial evaluation of vulnerability based on existing information and expert input. Users are encouraged to refer to the Template for Assessing Climate Change Impacts and Management Options (TACCIMO, http://www.taccimo.sgcp.ncsu.edu/) website for the most current peer-reviewed literature on a particular resource. This synthesis is a living document that can be revised and expanded upon as new information becomes available.

Geographic Scope

The project centers on the Sierra Nevada region of California, from foothills to crests, encompassing ten national forests and two national parks. Three geographic sub-regions were identified: north, central, and south. The north sub-region includes Modoc, Lassen, and Plumas National Forests; the central sub-region includes Tahoe, Eldorado, and Stanislaus National Forests, the Lake Tahoe Basin Management Unit, and Yosemite National Park; and the south sub-region includes Humboldt-Toiyabe, Sierra, Sequoia, and Inyo National Forests, and Kings Canyon/Sequoia National Park.

Key Definitions

Vulnerability: Susceptibility of a resource to the adverse effects of climate change; a function of its sensitivity to climate and non-climate stressors, its exposure to those stressors, and its ability to cope with impacts with minimal disruption[3].

Sensitivity: A measure of whether and how a species or system is likely to be affected by a given change in climate or factors driven by climate.

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[1] From California Wildlife Habitat Relationship (CWHR) habitat classification scheme http://www.dfg.ca.gov/biogeodata/cwhr/wildlife_habitats.asp

[2] For a list of participant agencies, organizations, and universities please refer to the final report *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada* available online at: http://ecoadapt.org/programs/adaptation-consultations/calcc.

[3] Glick, P., B.A. Stein, and N.A. Edelson, editors. 2011. Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment. National Wildlife Federation, Washington, D.C.

Adaptive Capacity: The degree to which a species or system can change or respond to address climate impacts.

Exposure: The magnitude of the change in climate or climate driven factors that the species or system will likely experience.

Methodology

The vulnerability assessment comprises three vulnerability components (i.e., sensitivity, adaptive capacity, and exposure), averaged rankings for those components, and confidence scores for those rankings (see tables below). The sensitivity, adaptive capacity, and exposure components each include multiple finer resolution elements that were addressed individually. For example, sensitivity elements include: direct sensitivity of the system to temperature and precipitation, sensitivity of component species within the system, ecosystem sensitivity to disturbance regimes (e.g., wind, drought, flooding), sensitivity to other climate and climate-driven changes (e.g., snowpack, altered hydrology, wildfire), and sensitivity to non-climate stressors (e.g., grazing, recreation, infrastructure). Adaptive capacity elements include: ecosystem extent, integrity, and fragmentation; ecosystem ability to resist or recover from stressors; landscape permeability; ecosystem diversity (e.g., physical, topographical, component species, functional groups); and ecosystem value and management potential. To assess exposure, participants were asked to identify the climate and climate-driven changes most relevant to consider for the ecosystem and to evaluate exposure to those changes for each of the three Sierra Nevada geographic sub-regions. Climate change projections were provided to participants to facilitate this evaluation[4]. For more information on each of these elements of sensitivity, adaptive capacity, and exposure, including how and why they were selected, please refer to the final methodology report *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada*[5].

During the workshop, participants assigned one of three rankings (High (>70%), Moderate, or Low (<30%)) to each finer resolution element and provided a corresponding confidence score (e.g., High, Moderate, or Low) to the ranking. These individual rankings and confidence scores were then averaged (mean) to generate rankings and confidence scores for each vulnerability component (i.e., sensitivity, adaptive capacity, exposure score) (see table below). Results presented in a range (e.g. from moderate to high) reflect variability assessed by participants. Additional information on ranking and overall scoring can be found in the final methodology report *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada*[5].

Recommended Citation

Hauptfeld, R.S., J.M. Kershner, and K.M. Feifel, eds. 2014. Sierra Nevada Ecosystem Vulnerability Assessment Technical Synthesis: Wet Meadows *in* Kershner, J.M., editor. 2014. *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada*. Version 1.0. EcoAdapt, Bainbridge Island, WA.

This document is available online at EcoAdapt (http://ecoadapt.org/programs/adaptation-consultations/calcc).

[4] Geos Institute. 2013. *Future Climate, Wildfire, Hydrology, and Vegetation Projections for the Sierra Nevada, California: A climate change synthesis report in support of the Vulnerability Assessment/Adaptation Strategy process.* Ashland, OR. http://ecoadapt.org/programs/adaptation-consultations/calcc.

[5] Kershner, J.M., editor. 2014. *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada.* Version 1.0. EcoAdapt, Bainbridge Island, WA. http://ecoadapt.org/programs/adaptation-consultations/calcc.

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Overview of Vulnerability Component Evaluations

SENSITIVITY

Sensitivity Factor	Sensitivity Evaluation	Confidence
Direct Sensitivities – Temperature	**1 Low**	**2 Moderate**
Direct Sensitivities – Precipitation	**3 High**	**2 Moderate**
Component Species	**2 Moderate**	**2 Moderate**
Disturbance Regimes	**3 High**	**3 High**
Climate-Driven Changes	**3 High**	**3 High**
Non-Climatic Stressors – Current Impact	**3 High**	**3 High**
Non-Climatic Stressors – Influence Overall Sensitivity to Climate	**3 High**	**3 High**
Other Sensitivities	**3 High**	**No answer provided by participants**

Overall Averaged Confidence (Sensitivity)[6]: Moderate-High

Overall Averaged Ranking (Sensitivity)[7]: Moderate–High

ADAPTIVE CAPACITY

Adaptive Capacity Factor	Adaptive Capacity Evaluation	Confidence
Extent and Integrity – Distribution	**3 High**	**3 High**
Extent and Integrity – Fragmentation	**3 High**	**3 High**
Resistance and Recovery	**2 Moderate**	**2 Moderate**
Landscape Permeability	**1 Low**	**3 High**
System Diversity – Physical/Topographical	**Low and High**	**2 Moderate**
System Diversity – Component Species/Functional Groups	**3 High**	**2 Moderate**
System Value	**3 High**	**3 High**
Specificity of Management Rules	**3 High**	**No answer provided by participants**
Other Adaptive Capacities	**No answer provided by participants**	**3 High**

Overall Average Confidence (Adaptive Capacity)[6]: Moderate-High

Overall Averaged Ranking (Adaptive Capacity)[7]: Moderate

EXPOSURE

Relevant Exposure Factor	Confidence
Climatic water deficit	**2 Moderate**
Snowpack	**2 Moderate**
Runoff	**1 Low**

[6] 'Overall averaged confidence' is the mean of the entries provided in the confidence column for sensitivity, adaptive capacity, or exposure, respectively.

[7] 'Overall averaged ranking' is the mean of the perceived rank entries provided in the respective evaluation column.

Relevant Exposure Factor	Confidence
Timing of flows	**2 Moderate**
Low flows	**2 Moderate**
High flows	**3 High**

Exposure Region	Exposure Evaluation (2010-2080)	Confidence
Northern Sierra Nevada	**2.5 Moderate–High**	**2 Moderate**
Central Sierra Nevada	**2.5 Moderate–High**	**2 Moderate**
Southern Sierra Nevada	**2 Moderate**	**2 Moderate**

Overall Averaged Confidence (Exposure)[6]: Moderate

Overall Averaged Ranking (Exposure)[7]: Moderate–High

Sensitivity

1. Direct sensitivities to changes in temperature and precipitation.

a. Sensitivity to temperature (means & extremes): Low
   i. Participant confidence: Moderate

b. Sensitivity to precipitation (means & extremes): High
   i. Participant confidence: Moderate

Additional comments: This system does not inhabit narrow climatic zones, but is mostly found above 1219 m (4000 ft) in the northern Sierra Nevada, and above 1524 m (5000 ft) in the southern Sierra Nevada.

References:

Temperature: Warmer temperatures will increase evapotranspiration rates, increasing groundwater extraction and the drying of meadows during warmer months (Stillwater Sciences 2012).

Precipitation: Meadow distribution, type and vegetation density are primarily determined by hydrology (Ratliff 1985; Weixelman et al. 2011; Viers et al. 2013). Wet meadows, for example, are found where the groundwater table depth during the growing season is approximately 0-40 cm deep; mesic meadows at 40-100 cm; and dry meadows where the water table is below 100 cm (Chambers et al. 2011; Lord et al. 2011). A high groundwater table is essential for meadow plants, which often have elevated rates of transpiration (Elmore et al. 2006; Loheide and Gorelick 2007). Wet meadows are highly sensitive to changes in snowmelt (Stillwater Sciences 2012), precipitation, groundwater and hydrology (Cooper and Wolf 2006, Loheide et al. 2009; Howard and Merrifield 2010; Viers et al. 2013) and particularly to the amplitude, duration and timing of surface and subsurface flows (Viers et al. 2013). Peat soil meadows require the buildup of soils with high organic matter and moisture; they take hundreds to thousands of years to develop but can be lost through drying and oxidation in years to decades (Stillwater Sciences 2012).

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2. Sensitivity of component species.

a. Sensitivity of component species to climate change: Moderate
   i. Participant confidence: Moderate

Additional comments: Component species include sedges, rushes and grasses, willows and other deciduous shrubs, forbs, amphibians, birds, fish, and insects. However, the composition of meadow species is less important to meadow classification than its structure and function, and meadows are very sensitive to drying, and potential extreme temperatures. Meadows are also sensitive to non-climate stressors.

References: According to an analysis by Gardali et al. (2012), bird taxa in wetlands are the most vulnerable, while bird taxa in grassland and oak woodland habitats are the least vulnerable to climate change in California. Reduced snowpack in the Sierra Nevada, together with earlier, more rapid snowmelt could have substantial effects on meadow-nesting birds (Siegel et al. 2008). Small or young birds may be particularly vulnerable to dehydration during extreme heat waves because of their limited water storage capacity, and, for nestlings, their lack of access to water (Perry et al. 2012). Further loss, degradation, and fragmentation of riparian areas, may not only affect breeding and wintering populations of many bird species but may also disrupt migration (loss of stopover habitat) and precipitate further population declines of species such as the endangered southwestern willow flycatcher (*Empidonax traillii extimus*), which requires moist habitats (Finch and Stoleson 2000), and yellow-billed cuckoo (*Coccyzus americanus*), which requires large patches of suitable riparian wooded habitat (Finch et al. 2012).

Please see the documents on focal species Willow flycatcher and Aspen for additional information.

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3. Sensitivity to changes in disturbance regimes.

a. Sensitivity to disturbance regimes including: Wildfire, drought, flooding, other – succession
b. Sensitivity to these disturbance regimes: High
    i. Participant confidence: High

Additional comments: Wet meadows are projected to be less sensitive in the short-term, however, over the longer-term, prolonged drought may enable tree and shrub encroachment into meadows. Change in snowmelt timing and amplitude may also have a large impact on meadows. For example, meadows are sensitive to extreme floods (e.g. rain on snow), which can wash out meadows and exacerbate stream incision and down-cutting. Meadows are not directly sensitive to changes in fire frequency or severity but fire suppression can aid conifer encroachment. Amphibians are sensitive to changes in disease regimes.

References:

Wildfire: Fire on the edge of the meadow/forest border can help the meadow to expand its range further into the area formally occupied by the forest (Ratliff 1985). Stand replacing fires upstream of a meadow can diminish evapotranspiration losses to upstream vegetation and cause temporary surface and groundwater increases for a few years following a fire. Large fires can also increase the amount and alter the type of sediments that are delivered to a meadow (Stillwater Sciences 2012).

Drought: Alder have deeper roots than willows and can survive multiple years of drought (Stillwater Sciences 2012). Prolonged drought and altered hydrology may enable tree and shrub encroachment (Millar et al. 2004).

Flashy precipitation events: Extreme precipitation can lead to flood events and threatens stream incision, down-cutting, loss of moist peat, and drying (Micheli and Kirchner 2002; Weixelman et al. 2011; Austin 2012; Viers et al. 2013). Sedge and rush rooting structures create more erosion resistance to channel banks than do grass species (Micheli and Kirchner 2002).

Succession: In some areas, trees are colonizing historically subalpine meadows (Millar et al. 2004). Subalpine meadows in the Sierra Nevada have been experiencing episodic invasion of pine during the 20th century, changing from meadows previously dominated by grasses, sedges and forbs, and displaying abrupt borders with surrounding forest, to having less distinct borders, with pines scattered throughout the meadow (Millar et al. 2004; Stillwater Sciences 2012). Lodgepole seedling establishment may also be favored in years with low snowpack and early snowmelt (Ratliff 1985).

(Please refer to Null et al. 2010 for a discussion on differential watershed responses across the Sierra Nevada).

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4. Sensitivity to other types of climate and climate-driven changes.

a. Sensitivity to climate and climate-driven changes including: Altered fire regimes, evapotranspiration and soil moisture, altered hydrology, extreme precipitation events
b. Sensitivity to these climate and climate-driven changes: High
    i. Participant confidence: High

Additional comments: Meadows are highly sensitive to extreme precipitation events, stream isolation, and altered hydrology, particularly the amplitude, duration, and timing of run-off. Altered hydrology, in part due to changes from snow to rain, may lead to channel erosion, meadows shrinking, and meadow conversion to trees and shrubs at both high and low elevations.

In addition, insects and fish are sensitive to changes in water temperature, and amphibians are sensitive to air pollution/ozone.

References identified by participants: Loheide et al. 2009; Cooper and Wolf 2006; Howard and Merrifield 2010; and Viers et al. 2013.

References:
Altered fire regimes: Reduced frequency of low intensity fire in meadows may partially explain the recent trend of conifer encroachment observed in meadows (Stillwater Sciences 2012). Over time, the willow and alder thickets typically found along the meadow-forest boundary are being replaced with dense under- and mid-story fir trees (Stillwater Sciences 2012). Fire suppression may indirectly reduce soil moisture in downstream meadows if upstream forests become dense and increase their evapotranspiration rate, and may contribute to conifer encroachment in meadows (Stillwater Sciences 2012).

Evapotranspiration and soil moisture: Evapotranspiration rates depend on temperature, relative humidity, rooting depth, water table and vegetation cover. Sedges and other wet plant species tend to have a higher evapotranspiration rate relative to mesic and dry meadow plants (Stillwater Sciences 2012).

Altered hydrology: The majority of inflowing water enters meadow systems as surface runoff in streams, groundwater or through the infiltration of direct precipitation. Many meadows are snowmelt dependent systems, and reduction in spring snowpack, or change in the ratio of snow to rain precipitation could convert some wet meadows to drier systems (Stillwater Sciences 2012).

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5. Sensitivity to impacts of other non-climate stressors.

a. Sensitivity to other non-climate stressors including: Agriculture and aquaculture, energy production and mining, transportation and service corridors, human intrusions and disturbance, invasive species, other – water diversions
b. Current effects of these identified stressors on system: High
    i. Participant confidence: High
c. Degree stressors increase sensitivity to climate change: High
    i. Participant confidence: High

Additional comments: Among the available categories, participants selected ‘agriculture and aquaculture’ to reflect grazing of horses and cows, and the category ‘energy production and mining’ to reflect the stressors of dams and water storage, especially in the northern Sierra Nevada. The participants also chose ‘transportation and service corridors’ to reflect the stressors of roads and culverts; the category ‘human intrusions and disturbance’ to reflect recreation impacts; and ‘invasive species’ to reflect grasses, particularly *Poa pratensis*.

Channel incision, gullying, or other modifications to a meadow’s hydrology can be highly destructive. These features can alter the groundwater level in meadows, as well as the rate of water transport away from meadows, altering seasonal overflow patterns. Stream incisions are also formed as a secondary effect of grazing, rail and auto grades, culverts, and extreme high flows.

Roads or trails are commonly installed near or in meadows, because meadows often form in the flatlands or valleys. The construction of roads can cause localized compaction of soil, which reduces water holding capacity and infiltration, and once installed, roads adjacent to meadows can increase surface runoff, which can increase localized erosion. Use of off-roading vehicles where roads are not installed can also damage meadows due to soil compaction.

The disturbance of construction can also serve as vectors for the introduction of non-native species, as can hikers on recreational trails, while construction of trails and campsites may fragment meadows.

The conversion of forested lands to residential or commercial developments has been a primary cause of destruction to Sierra Nevada meadows. Meadows and rivers are considered prime locations for human settlements and these developments often destroy meadows. Hardened surfaces can reduce the amount of groundwater recharge, altering the hydrology and likely reducing the water availability of downstream meadows.

References:
Natural system modification: Meadow sensitivity may be exacerbated by the current impacted state of meadows (Loheide et al. 2009). In six National Forests in the Sierra Nevada and Southern Cascade ranges, 46% of riparian meadows are not significantly incised while 54% are (Living Assessment 2013).

Agriculture and aquaculture: Livestock grazing causes soil compaction and channel incision, lowering streambeds and groundwater tables (Stillwater Sciences 2012), and potentially exacerbating the hydrologic changes anticipated with climate change. Grazing causes permanent changes to features of meadows such as compacting of soil, increase in erosion, and channel incision (Ratliff 1985). In a study of 24 meadows that were open to cattle grazing, located on the western slope of the central Sierra Nevada at elevations of 2200-2700 m (7217-8858 ft), cattle use was negatively correlated to meadow wetness (Roche et al. 2012). At higher elevation meadows, packstock associated with recreational activities may have greater impact than feedstock due in part to soil compaction, along with campgrounds (Menke et al. 1996 cited in Stillwater Sciences 2012). A list of primary research on grazing impacts in meadows can be found in Stillwater Sciences (2012).

Invasive and other problem species: Invasive and non-native plant species often invade meadows after a soil disturbance. Some of these plants have a shallow root system, which can enhance localized erosion. High elevation Sierra Nevada meadows have a low occurrence of non-native species (D'Antonio et al. 2004).

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6. Other sensitivities.

a. Other critical sensitivities not addressed: Connectivity
   i. Participant confidence: no answer provided by participants
b. Collective degree these factors increase system sensitivity to climate change: High

Additional comments: Meadows and fens are sensitive to climate change due to a lack of connectivity among sites. They have limited ability to move or shift upslope and it takes thousands of years to form new meadows naturally. Loss of peat in fens occurs due to lower water, higher evapotranspiration and oxidation.

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7. Overall user ranking.

a. Overall sensitivity of this system to climate change: High
   i. Participant confidence: no answer provided by participants

Additional comments: This system is highly sensitive to climate change and other non-climate stressors primarily as a result of its dependence on water, fragmented ownership pattern with relatively high percentage in private ownership, its current degraded state, and inability to shift upslope.

Adaptive Capacity

1. **System extent and integrity.**
   a. System extent throughout the Sierra Nevada (widespread to narrow distribution): High
      i. Participant confidence: High
   b. Level of fragmentation across the Sierra Nevada: High
      i. Participant confidence: High

Additional comments: Meadows occur across the Sierra Nevada, but are one of the rarest and most isolated/fragmented habitat types in the Sierra Nevada. They represent a tiny fraction of the land base (~1%), and as such are patchy in distribution.

References:
Geographic extent: Meadows are well distributed across the Sierra at different elevations (Whitney 1979) but are among the rarest and most isolated habitat types in the Sierra Nevada, representing approximately 1% of the land base (Davis and Stoms 1996; Viers et al. 2013). The non-uniform distribution and lack of connectivity between meadows may exacerbate the effects of altered hydrology (Viers et al. 2013).

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2. **Resistance, recovery, and refugia.**
   a. Ability of system to resist or recover from impacts: Moderate
      i. Participant confidence: Moderate
   b. Suitable microclimates within the system that could support refugial communities: There are regional differences in meadows between north, central and south Sierra Nevada. Refugia could be possible at elevational zones with stable climates. Meadows that currently occur at elevations where future predicted snowpack is projected to be retained may be more resilient to future climate conditions. Meadows within predicted climate refugia (cold sinks) and fed by northerly exposed watersheds may also be more resilient to future conditions. Wetter meadows and fens may be more stable and able to resist climate impacts and conifer encroachment, and resilient to an increase in extreme flow events if they are found in a healthy state. In contrast, meadows with altered hydrologic function (isolated floodplains) will be less resilient to climate impacts and less able to recover from extreme events or adapt to changing conditions.

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3. **Landscape permeability.**
   a. Degree of landscape permeability: Low
      i. Participant confidence: High
   b. Potential types of barriers to dispersal that apply: geologic features, other – natural topography

Additional comments: Geologic features are identified as barriers to dispersal, and include soil types and basin shape and depth. Concerns exist regarding landscape permeability, since upslope shifts are unlikely, given the complexity of mountain basins. Groundwater-fed systems (e.g. those associated with volcanic soils in the southern Cascades) may be more resilient to climate impacts.

References: Although meadows occur within a diverse range of elevations (Whitney 1979), permeability across the landscape is limited by topography and geologic features, including soil type, basin shape and depth, and slope (Weixelman et al. 2011). Non-uniform distribution and lack of connectivity may exacerbate sensitivity of meadows to altered hydrology (Viers et al. 2013).

4. **System diversity.**
    a. Level of physical and topographic diversity: Physical – Low; Topographic – High
        i. Participant confidence: Moderate
    b. Level of component species/functional group diversity: High
        i. Participant confidence: Moderate
    c. Description of diversity: The participants marked both Low and High for Question 4a (above) to reflect the low diversity of slopes on which meadows and fens are found, and the high diversity of elevations and soils on which they occur. Meadows exhibit multiple vegetation types and hydrologic processes, and high floral and faunal diversity. Meadows are dominated by graminoids and forbs, and natural oscillation of dominant groups in meadows depends on multiple factors, especially hydrology, soils, elevation, and current and past disturbance (e.g. grazing). Wetter, more stable meadows tend towards dominance by sedges and rushes, while drier sites and those with significant disturbance tend towards dominance by forbs. Shifts from rhizomatous species to annuals would be problematic, increasing erosion potential.

References identified by participants: Weixelman et al. 2011.

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5. **Management potential.**
    a. Value level people ascribe to this system: High
        i. Participant confidence: High
    b. Specificity of rules governing management of the system: High
        i. Participant confidence: no answer provided by participants
    c. Description of use conflicts: Grazing and stock use; recreation; non-native fisheries; water rights and water use issues (some users don't want water held in meadows).
    d. Potential for managing or alleviating climate impacts: There is high restoration potential for meadows. Management can include engineered solutions, and management options may include moving trails, campsites, roads away from meadows, and most importantly, restoring floodplain connectivity. Fens may be harder to restore when degraded.

Additional comments: There are lots of historic uses which hinder management, making planning for meadows and fens complicated. For example, grazing is frequently grandfathered in management policies, and recent concerns of water rights and fish may hamper future meadow restoration options. The specificity of regulations regarding meadow management by the USFS is relatively low. Utilization by livestock is the primary element guiding management. There is very little oversight of NEPA for meadow management by USFS or environmental groups.

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6. **Other adaptive capacity factors.**
    a. Additional factors affecting adaptive capacity: See comment below
        i. Participant confidence: no answer provided by participants
    b. Collective degree these factors affect the adaptive capacity of the system: no answer provided by participants

Additional comments: Groundwater recharge relates to hydrologic regime and topography, as well as to the surrounding vegetation and evapotranspiration.

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7. **Overall user ranking.**

a. <u>Overall adaptive capacity of the system</u>: Low *and* Moderate (depending on management)
    i. Participant confidence: no answer provided by participants

Additional comments: The participants rate the adaptive capacity of meadows 'low' without management, but 'moderate' with focused management and restoration. Without management intervention, meadows and fens cannot move and are limited in the landscape. Meadows are already stressed and highly degraded and management potential is expensive and limited by private ownership. However, restoration can result in recovery and is currently being practiced throughout the Sierra, so the body of knowledge on restoring these systems is increasing.

References: Despite the high level of projected climate stress, California has landscape features that may reduce exposure of species to climate change, including high topographic diversity, abundant perennial water sources, broad elevation and climatic gradients, and long riparian corridors (Klausmeyer et al. 2011).

Exposure

1. Exposure factors[8].

a. Factors likely to be most relevant or important to consider for the system: Climatic water deficit, snowpack, runoff, timing of flows, low flows, high flows

i. Confidence: Moderate (climatic water deficit); Moderate (snowpack); Low (runoff); Moderate (timing of flows); Moderate (low flows); High (high flows)

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2. Exposure region.

a. Exposure by region: North – Moderate-High; Central – Moderate-High; South – Moderate

i. Participant confidence: Moderate (all)

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3. Overall user ranking.

a. Overall perceived exposure of the species to climate changes: High

i. Participant confidence: Moderate

References identified by participants: Austin 2012.

References:

Temperature: Over the next century, temperatures in California are expected to rise (Hayhoe et al. 2004: Cayan et al. 2008), with the lower range of warming projected between 1.7-3.0°C, 3.1-4.3°C in the medium range, and 4.4-5.8°C in the high range (Cayan et al. 2008). Temperatures along the western slope of the Sierra Nevada are forecast to increase between 0.5-1°C by 2049, and 2-3°C by 2099 (Das et al. 2011). On average, summer temperatures are expected to rise more than winter temperatures throughout the Sierra Nevada region (Hayhoe et al. 2004; Cayan et al. 2008; Geos Institute 2013). Temperature projections using global coupled ocean-atmospheric models (GDFL[9] and PCM[10]) predict summer temperatures to increase 1.6-2.4˚C by mid- century (2049), with the least increases expected in the northern bioregion, and greatest increases expected in the southern bioregion (Geos Institute 2013). By late century (2079), summer temperatures are forecast to increase 2.5-4.0˚C, with changes of least magnitude occurring in the central bioregion (Geos Institute 2013). Winter temperatures are forecast to increase 2.2-2.9˚C by late century (2079), with changes of least magnitude occurring in the central bioregion (Geos Institute 2013). Associated with rising temperatures will be an increase in potential evaporation (Seager et al. 2007).

Scenarios modeling increased atmospheric temperatures at 2°C, 4°C and 6°C run by Null et al. (2010) forecast that, overall, watersheds in the northern Sierra Nevada are most vulnerable to decreased mean annual flow, southern-central watersheds are most susceptible to runoff timing changes, and the central portion of the range is most affected by longer periods with low flow conditions.

Precipitation: Precipitation has increased slightly (~2%) in the Sierra Nevada over the past 30 years compared with a mid-twentieth century baseline (1951-1980) (Flint et al. 2013). Projections for future precipitation in the Sierra Nevada vary among models; some demonstrate little to no change (e.g. PCM) while others demonstrate more substantial changes (e.g. GFDL). In general, annual precipitation is projected to exhibit only modest changes by the end of the century (Hayhoe et al. 2004; Dettinger 2005;

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[8] Participants were asked to identify exposure factors most relevant or important to the species but were not asked to evaluate the degree to which the factor affects the species.

[9] Delworth, T. L., Broccoli, A. J., Rosati, A. et al. (2006) GFDL's CM2 Global Coupled Climate Models. Part I: Formulation and Simulation Characteristics. Journal of Climate, 19:643-674.

[10] Washington, W. M., Weatherly J. W., Meehl G. A. et al. (2000) Parallel climate model (PCM) control and transient simulations. Climate Dynamics 16:755-744.

Maurer 2007; Cayan et al. 2008; Geos Institute 2013), with some precipitation decreases in spring and summer (Cayan et al. 2008; Geos Institute 2013). Frequency of extreme precipitation, however, is expected to increase in the Sierra Nevada between 11-49% by 2049 and 18-55% by 2099 (Das et al. 2011). An increase in flashy precipitation events may lead to erosion of moist peat and topsoil due to flooding (Weixelman et al. 2011; Viers et al. 2013), as well as drying of meadows caused by channel incision (Viers et al. 2013).

Snow volume and timing: Overall, April 1st snowpack in the Sierra Nevada, calculated as snow water equivalent (SWE), has seen a reduction of 11% in the last 30 years (Flint et al. 2013), as a consequence of earlier snowmelt (Cayan et al. 2001; Stewart et al. 2005; Hamlet et al. 2007), increased frequency of melt events (Mote et al. 2005), and increased rain:snow ratio (Knowles et al. 2006). However, trends in snowpack in the Sierra Nevada have displayed a high degree of interannual variability and spatial heterogeneity (Mote et al. 2005; Safford et al. 2012). SWE in the southern Sierra Nevada has actually increased during the last half-century, due to increases in precipitation (Mote et al. 2005; Mote 2006; Moser et al. 2009; Flint et al. 2013).

Despite modest projected changes in overall precipitation, models of the Sierra Nevada region largely project decreasing snowpack (Miller et al. 2003; Dettinger et al. 2004b; Hayhoe et al. 2004; Knowles and Cayan 2004; Maurer 2007; Young et al. 2009) and earlier timing of runoff center of mass (Miller et al. 2003; Knowles and Cayan 2004; Maurer 2007; Maurer et al. 2007; Young et al. 2009), as a consequence of early snowmelt events and a greater percentage of precipitation falling as rain rather than snow (Dettinger et al. 2004a, 2004b; Young et al. 2009; Null et al. 2010).

Annual snowpack in the Sierra Nevada is projected to decrease between 64-87% by late century (2060-2079) (Thorne et al. 2012; Flint et al. 2013; Geos Institute 2013). Under scenarios of 2-6˚C warming, snowpack is projected to decline 10-25% at elevations above 3750 m (12303 ft), and 70-90% below 2000 m (6562 ft) (Young et al. 2009). Several models project greatest losses in snowmelt volume between 1750 m to 2750 m (5741 ft to 9022 ft) (Miller et al. 2003; Knowles and Cayan 2004; Maurer 2007; Young et al. 2009), because snowfall is comparatively light below that elevation, and above that elevation, snowpack is projected to be largely retained. The greatest declines in snowpack are anticipated for the northern Sierra Nevada (Safford et al. 2012), with the current patterns of snowpack retention in higher-elevation southern Sierra Nevada basins expected to continue through the end of the century (Maurer 2007). Greatest losses in snowmelt volume are expected between 1750 m to 2750 m (5741 ft to 9022 ft) (Miller et al. 2003; Knowles and Cayan 2004; Maurer 2007; Young et al. 2009), largely corresponding with the elevation where montane meadows occur.

Shifts from rain to snow are also largely expected between 1500 to 3000 m (4921 ft to 9843 ft) (Viers et al. 2013; Young et al. 2009), where the majority of montane meadows occur (Viers et al. 2013). Average fractions of total precipitation falling as rain in the Sierra Nevada can be expected to increase by approximately 10% under a scenario of 2.5˚C warming (Dettinger et al. 2004b). Increased rain:snow ratio and advanced timing of snowmelt initiation are expected to advance the runoff center of mass by 1-7 weeks by 2100 (Maurer 2007), although advances will likely be non-uniformly distributed in the Sierra Nevada (Young et al. 2009). Snow provides an important contribution to spring and summer soil moisture in the western U.S. (Sheffield et al. 2004), and earlier snowmelt can lead to an earlier, longer dry season (Westerling et al. 2006). A shift from snowfall to rainfall is also expected to result in flashier runoff with higher flow magnitudes, and may result in less water stored within watersheds, decreasing meal annual flow (Null et al. 2010). Mean annual flow is projected to decrease most substantially in the northern bioregion (Null et al. 2010).

Climatic water deficit: Increases in potential evapotranspiration will likely be the dominant influence in future hydrologic cycles in the Sierra Nevada, decreasing runoff even under forecasts of increased precipitation, and driving increased climatic water deficits (Thorne et al. 2012). Climatic water deficit, which combines the effects of temperature and rainfall to estimate site-specific soil moisture, is a function of actual evapotranspiration and potential evapotranspiration. In the Sierra Nevada, climatic water deficit has increased slightly (~4%) in the past 30 years compared with the 1951-1980 baseline (Flint et al. 2013). Future downscaled water deficit projections using the Basin Characterization Model (Thorne et al. 2012; Flint et al. 2013) and IPCC A2 emissions scenario predict increased water deficits (i.e., decreased soil moisture) by up to 44% in the northern Sierra Nevada, 38% in the central Sierra Nevada, and 33% in the southern Sierra Nevada (Geos Institute 2013).

Lower late-spring and summer flows on snow-melt rivers, and groundwater declines, may reduce survival and growth of shallow-rooted plants, such as seedlings and juveniles trees, as well as phreatophytic trees, when water tables drop too far or too quickly. Surviving phreatophytes may increase root depth in response to declining low flows, shifting plant community composition toward more drought tolerant native and introduced species (Shafroth et al. 2000, Rood et al. 2003, Rood et al. 2008, cited in Perry et al. 2012).

Many riparian plants are adapted to hydrologic and geomorphic disturbances and tolerate both seasonal and annual variation in environmental conditions (Naiman and Decamps 1997 cited in Seavey et al. 2009). Long-term reduction in sediment transport and deposition and rates of channel migration and abandonment eventually shrinks the areas where pioneer species establish (Scott et al. 1996, Friedman et al. 1998, Shafroth et al. 2002 cited in Perry et al. 2012).

Aspen (*Populus termuloides*): For more information on aspen and climate change exposure, please refer to the aspen document.

Willow flycatcher: For more information on willow flycatcher and climate change exposure, please refer to the willow flycatcher document.

More information on downscaled projected climate changes for the Sierra Nevada region is available in a separate report entitled *Future Climate, Wildfire, Hydrology, and Vegetation Projections for the Sierra Nevada, California: A climate change synthesis in support of the Vulnerability Assessment/Adaptation Strategy process* (Geos Institute 2013). Additional material on climate trends for the system may be found through the TACCIMO website (http://www.sgcp.ncsu.edu:8090/). Downscaled climate projections available through the Data Basin website (http://databasin.org/galleries/602b58f9bbd44dffb487a04a1c5c0f52).

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Literature Cited

Austin, J. T. (2012). Floods and Droughts in the Tulare Lake Basin. Three Rivers, CA, Sequoia Natural History Association.

Cayan, D., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio and D. H. Peterson (2001). "Changes in the Onset of Spring in the Western United States." Bulletin of the American Meteorological Society **82**(3): 399-145.

Cayan, D. R., E. P. Maurer, M. D. Dettinger, M. Tyree and K. Hayhoe (2008). "Climate change scenarios for the California region." Climatic Change **87**(S1): 21-42.

Chambers, J. C. and J. R. e. Miller (2011). Geomorphology, hydrology, and ecology of Great Basin meadow complexes - implications for management and restoration. General Technical Report, RMRS-GTR-258. Fort Collins, Colorado, USDA Forest Service, Rocky Mountain Research Station.

Cooper, D. J. and E. C. Wolf (2006). Fens of the Sierra Nevada, California. Final Report to the USDA Forest Service. **47**.

D'Antonio, C. M., E. L. Berlow and K. L. Haubensak (2004). Invasive Exotic Plant Species in Sierra Nevada Ecosystems. Albany, CA, US Department of Agriculture, Forest Service, Pacific Southwest Research Station. **Gen. Tech. Rep. PSW-GTR-193:** 175-184.

Das, T., M. D. Dettinger, D. R. Cayan and H. G. Hidalgo (2011). "Potential increase in floods in California's Sierra Nevada under future climate projections." Climatic Change **109**(S1): 71-94.

Davis, F. W. and D. M. Stoms (1996). Sierran vegetation: A gap analysis. Chap. 23. Sierra Nevada Ecosystem Project: Final report to Congress, vol. II, Davis: University of California, Centers for Water and Wildland Resources. .

Dettinger, M. D. (2005). "From climate-change spaghetti to climate-change distributions for 21st Century California." San Francisco Estuary and Watershed Science **3**(1): Article 4.

Dettinger, M. D., D. R. Cayan, N. Knowles, A. Westerling and M. K. Tyree (2004a). Recent Projections of 21st-Century Climate Change and Watershed Responses in the Sierra Nevada, USDA Forest Service. **Gen. Tech. Report PSW-GTR-193**.

Dettinger, M. D., D. R. Cayan, M. K. Meyer and A. E. Jeton (2004b). "Simulated Hydrologic Responses to Climate Variations and Change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900–2099." Climate Change **62**: 283-317.

Elmore, A. J., S. J. Manning, J. F. Mustard and J. M. Craine (2006). "Decline in alkali meadow vegetation cover in California: the effects of groundwater extraction and drought." Journal of Applied Ecology **43**(4): 770-779.

Finch, D. M., D. M. Smith, O. LeDee, J.-L. E. Cartron and M. A. Rumble (2012). Climate Change, Animal Species and Habitats: Adaptation and Issues. Climate change in grasslands, shrublands and deserts of the Interior American West: a review and needs assessment. . D. M. Finch, US Department of Agriculture Forest Service Rocky Mountain Research Station,. **Gen Tech Rep RMRS-GTR-285:** 139.

Finch, D. M. and S. H. Stoleson (2000). Status, ecology, and conservation of the southwestern willow flycatcher. General Technical Report, USDA Forest Service, Rocky Mountain Research Station. **RMRS-GTR-60**.

Flint, L. E., A. L. Flint, J. H. Thorne and R. Boynton (2013). "Fine-scale hydrologic modeling for regional landscape applications: the California Basin Characterization Model development and performance." Ecological Processes ***2***: 25.

Gardali, T., N. E. Seavy, R. T. DiGaudio and L. A. Comrack (2012). "A climate change vulnerability assessment of California's at-risk birds." PLoS One **7**(3).

Geos Institute (2013). Future Climate, Wildfire, Hydrology, and Vegetation Projections for the Sierra Nevada, California: A climate change synthesis in support of the Vulnerability Assessment/Adaptation Strategy (VAAS) process, Available online at: http://www.geosinstitute.org/climatewiseservices/completed-climatewise-projects.html.

Hamlet, A. F., P. W. Mote, M. P. Clark and D. P. Lettenmaier (2007). "Twentieth-Century Trends in Runoff, Evapotranspiration, and Soil Moisture in the Western United States*." Journal of Climate **20**(8): 1468-1486.

Hayhoe, K., D. Cayan, C. B. Field, P. C. Frumhoff, E. P. Maurer, N. L. Miller, S. C. Moser, S. H. Schneider, K. N. Cahill, E. E. Cleland, L. Dale, R. Drapek, R. M. Hanemann, L. S. Kalkstein, J. Lenihan, C. K. Lunch, R. P. Neilson, S. C. Sheridan and J. H. Verville (2004). "Emissions pathways, climate change, and impacts on California." Proceedings of the National Academy of Sciences **101**(34): 12422-12427.

Howard, J. and M. Merrifield (2010). "Mapping groundwater dependent ecosystems in California." PLoS One **5**(6): e11249.

Klausmeyer, K. R., M. R. Shaw, J. B. MacKenzie and D. R. Cameron (2011). "Landscape-scale indicators of biodiversity's vulnerability to climate change." Ecosphere **2**(8): art88.

Knowles, N. and D. Cayan (2004). "Elevational dependence of projected hydrologic changes in the San Francisco Estuary and Watershed." Climate Change **62**: 319-336.

Knowles, N., M. D. Dettinger and D. Cayan (2006). "Trends in Snowfall versus Rainfall in the Western United States." Journal of Climate **19**(18): 4545-4559.

Living Assessment. (2013). "Chapter 2 Bio-region: Sierra Nevada bio-region."   Retrieved Feb. 28 2013, from http://livingassessment.wikispaces.com/Chapter+2+Bio-region.

Loheide, S. P., R. S. Deitchman, D. J. Cooper, E. C. Wolf, C. T. Hammersmark and J. D. Lundquist (2009). "A framework for understanding the hydroecology of impacted wet meadows in the Sierra Nevada and Cascade Ranges, California, USA." Hydrogeology Journal **17**(1): 229-246.

Loheide, S. P. and S. M. Gorelick (2007). "Riparian hydroecology: A coupled model of the observed interactions between groundwater flow and meadow vegetation patterning." Water Resources Research **43**(7): n/a-n/a.

Lord, M., D. Jewett, J. R. Miller, D. Germanoski and J. C. Chambers (2011). Hydrologic processes influencing meadow ecosystems. Great Basin Riparian Ecosystems: Ecology, Management, and Restoration (Chp 4]. Geomorphology, hydrology, and ecology of Great Basin meadow complexes - implications for management and restoration. J. C. Chambers and J. R. Miller. Fort Collins, CO, USCA Forest Service Rocky Mountain Research Station. **Gen. Tech. Rep. RMRS-GTR-258:** 44-67.

Maurer, E. P. (2007). "Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios." Climatic Change **82**(3-4): 309-325.

Maurer, E. P., I. T. Stewart, C. Bonfils, P. B. Duffy and D. Cayan (2007). "Detection, attribution, and sensitivity of trends toward earlier streamflow in the Sierra Nevada." Journal of Geophysical Research **112**(D11).

McKenzie, D., Z. Gedalof, D. L. Peterson and P. W. Mote (2004). "Climate Change, Wildfire, and Conservation." Conservation Biology **18**(4): 890-902.

Micheli, E. R. and J. W. Kirchner (2002). "Effects of wet meadow riparian vegetation on streambank erosion. 2. Measurements of vegetated bank strength and consequences for failure mechanics." Earth Surface Processes and Landforms **27**(7): 687-697.

Millar, C. I., R. D. Westfall and D. L. Delaney (2004). "Response of Subalpine Conifers in the Sierra Nevada, California, U.S.A., to 20th-Century Warming and Decadal Climate Variability." Arctic, Antarctic, and Alpine Research **36**(2): 181-200.

Miller, N. L., K. E. Bashford and E. Strem (2003). "Potential impacts of climate change on California hydrology." Journal of American Water Resources Association **39**(4): 771-784.

Moser, S. C., G. Franco, S. Pittiglio, W. Chou and D. Cayan (2009). The Future Is Now: An Update On Climate Change Science Impacts And Response Options For California, Prepared for: California Energy Commission, Public Interest Energy Commission. **CEC-500-2008-071**.

Mote, P. W. (2006). "Climate-Driven Variability and Trends in Mountain Snowpack in Western North America." Journal of Climate **19**(23): 6209-6220.

Mote, P. W., A. F. Hamlet, M. P. Clark and D. P. Lettenmaier (2005). "Declining Mountain Snowpack in Western North America*." Bulletin of the American Meteorological Society **86**(1): 39-49.

Null, S. E., J. H. Viers and J. F. Mount (2010). "Hydrologic response and watershed sensitivity to climate warming in California's Sierra Nevada." PLoS One **5**(4).

Perry, L. G., D. C. Andersen, L. V. Reynolds, S. M. Nelson and P. B. Shafroth (2012). "Vulnerability of riparian ecosystems to elevated CO2 and climate change in arid and semiarid western North America." Global Change Biology **18**(3): 821-842.

Ratliff, R. D. (1985). Meadows in the Sierra Nevada of California: state of knowledge. Berkeley, CA, USDA Forest Service. **Gen. Tech. Rep. PSW 84:** 52.

Roche, L. M., K. J. Rice and K. W. Tate (2012). "Oak conservation maintains native grass stands in an oak woodland-annual grassland system." Biodiversity and Conservation **21**(10): 2555-2568.

Safford, H., M. North and M. D. Meyer (2012). Chapter 3: Climate Change and the Relevance of Historical Forest Condition. Managing Sierra Nevada Forests, USDA Forest Service, Pacific Southwest Research Station. **Gen. Tech. Rep. PSW-GTR-237**.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H. P. Huang, N. Harnik, A. Leetmaa, N. C. Lau, C. Li, J. Velez and N. Naik (2007). "Model projections of an imminent transition to a more arid climate in southwestern North America." Science **316**(5828): 1181-1184.

Sheffield, J., G. Goteti, F. Wen and E. F. Wood (2004). "A simulated soil moisture based drought analysis for the United States." Journal of Geophysical Research: Atmospheres (1984-2012) **109(D24)**.

Siegel, R. B., R. L. Wilkerson and D. F. DeSante (2008). "Extirpation of the willow flycatcher from Yosemite National Park." Western Birds **39**: 8 – 21.

Stewart, I., D. Cayan and M. D. Dettinger (2005). "Changes toward Earlier Streamflow Timing across Western North America." Journal of Climate **18**: 1136-1155.

Stillwater Sciences (2012). A Guide for Restoring Functionality to Mountain Meadows of the Sierra Nevada. Technical Memorandum, Prepared by Stillwater Sciences, Berkeley, CA, for American Rivers, Nevada City, CA.

Thorne, J. H., R. Boynton, L. Flint, A. Flint and T.-N. G. Le (2012). Development and Application of Downscaled Hydroclimatic Predictor Variables for Use in Climate Vulnerability and Assessment Studies, Prepared for California Energy Commission, Prepared by University of California, Davis. **CEC-500-2012-010**.

Viers, J. H., S. E. Purdy, R. A. Peek, A. Fryjoff- Hung, N. R. Santos, J. V. E. Katz, J. D. Emmons, D. V. Dolan and S. M. Yarnell (2013). Montane Meadows In The Sierra Nevada: Changing Hydroclimatic Conditions And Concepts For Vulnerability Assessment, Center for Watershed Sciences Technical Report. **CWS-2013-01**.

Weixelman, D. A., B. Hill, D. J. Cooper, E. L. Berlow, J. H. Viers, S. Purdy, A. G. Merril and S. Gross (2011). Meadow Hydrogeomorphic Types for the Sierra Nevada and Southern Cascade Ranges in California, US Department of Agriculture, Forest Service, Pacific Southwest Region. **Gen. Tech. Rep. R5-TP-034:** 34.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan and T. W. Swetnam (2006). "Warming and earlier spring increase western U.S. forest wildfire activity." Science **313**: 940-943.

Whitney, S. (1979). A Sierra Club naturalist's guide to the Sierra Nevada. San Francisco, Sierra Club Books.

Young, C. A., M. I. Escobar-Arias, M. Fernandes, B. Joyce, M. Kiparsky, J. F. Mount, V. K. Mehta, D. Purkey, J. H. Viers and D. Yates (2009). "Modeling The Hydrology Of Climate Change In California's Sierra Nevada For Subwatershed Scale Adaptation." Journal of American Water Resources Association **45**(6): 1409-1423.

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