CalVeg types included: **WTM**-Wet meadow: Sedge species (*Carex spp*.), rush species (*Juncus spp.*), tufted hairgrass (*Deschampsia cespitosa*); **MRI**-Montane riparian: Black cottonwood (*Populus balsamifera*), bigleaf maple (*Acer macrophyllum*), white alder (*Alnus rhombifolia*); **PGS**-Perennial grassland: California oatgrass (*Danthonia californica*), hairgrass (*Deschampsia cespitosa*), sweet vernalgrass (*Anthoxanthum odoratum*)

Sensitivity Assessment

1. Direct Sensitivities

- Temperature
    - Means and extremes
        - Historical
        - Future
            - Over the next century, average temperatures are expected to increase by 2-4 ^{o}F in winter and 4-8 ^{o}F in the summer. Models indicate that there may be less warming along the southwest coast but more warming to the north and northeast (Hayhoe et al., 2004).
    - System's sensitivity, composition and response to temperature
        - Warmer temperatures will increase evapotranspiration rates, increasing groundwater extraction and the drying of meadows during warmer months.
- Precipitation
    - Means and extremes
        - Historical
        - Future
    - System's sensitivity, composition and response to precipitation
        - A meadow's distribution, type and density of vegetation is mainly a function of water availability. Wet meadows are found when the depth of the groundwater table is 0-15 cm depth, mesic meadows occur when the groundwater is 50 cm depth, dry meadows at 100-150 cm and sage meadow at 150-250 cm depth. (Stillwater Sciences, 2012).

2. Sensitivity of Component Species

- Dominant species
    - Riparian meadows are dominated by sedges, grasses, forbs, and yarrow. Lodgepole pine, willow, alder, and current can be present but are usually not dominant.
- Ecosystem engineers
    - The deep-rooted sedges can help to reduce erosion.
- Keystone species

3. Indirect Sensitivities

- Wildfire
  - During years with normal amounts or precipitation, meadows are generally moist enough to not burn in fires. However, if there is no grazing and grasses grow tall and there is a corresponding drought, meadows may burn. Light fires across meadows appear to have a minimal effect on vegetative composition but hot fires can cause extreme disruption. 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).
- Disease
- Flooding
  - Erosion in meadows can be detrimental to the health of meadows because the moist peat and top-soil are integral to the development of meadows. Sedge and rush rooting structures create more erosion resistance to channel banks than do grass species (Micheli, 2002). Under most climate scenarios, runoff and potential flooding in the winter and early spring is expected to be higher than historical norms due to earlier snowmelt coupled with enhanced rainfall (Miller, 2003).
- Insects
- Wind
- Drought
  - The depth of a plant's roots can be a strong indicator of its sensitivity to drought. Willows and other densely rooting riparian shrubs can survive short periods of drought. Alder have deeper roots relative to willows and can survive multiple years of drought (Stillwater Sciences, 2012)

4. Sensitivity to other Climate Impacts

- Altered hydrology
  - The majority of inflowing water enters as surface runoff in streams, groundwater or through the infiltration of direct precipitation. Many meadows are snowmelt dependent systems so reduction in spring snowpack in the future or the fraction of snow to rain precipitation could convert some wet meadows to drier systems (Stillwater Sciences, 2012). Over the past 50 years, spring snowpack in the Sierra Nevada has decreased by 70-120% although there is a high degree of spatial heterogeneity; snowpack in the southern portion of the Sierra Nevada has increased. The reduction in snowpack will likely be greater at lower elevations in northern Sierra than in the higher elevations in the southern Sierra. Annual

snowpack in the Sierra Nevada could decrease by 20-90% due to future climate change (Safford, 2010).

- Altered fire regimes
  - Over the past 100 years, fire has been greatly suppressed in meadows. Historically, Native Americans used to burn meadows every 10-12 years to reduce tree encroachment and to promote the growth of preferred vegetation. The reduced frequency of low intensity fire in meadows may partially explain the recent trend of conifer encroachment seen in meadows. 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)
- Evapotranspiration and soil moisture
  - Water retention in meadows is a function of the thickness and porosity of the surrounding sediments as well as the groundwater hydraulic gradient which can change seasonally (away from channel during wet period = groundwater recharge, toward channel during summer and fall).
  - Evapotranspiration rate depends on temperature, relative humidity, rooting depth, water table and vegetation cover. Climate change is expected to cause warmer temperatures hence, evapotranspiration rates will likely increase in meadows. Sedges and other wet plant species tend to have a higher evapotranspiration rate relative to mesic and dry meadow plants. Replanting wet plant species in a relatively dry site can increase net water loss from the meadow due to evapotranspiration. If an upstream forest has become too dense due to fire suppression it can result in an increased relative evapotranspiration which reduces the amount of groundwater that will reach the downstream meadow. (Stillwater Sciences, 2012)
- Extreme precipitation and temperature
  - In general, most models predict that the frequency of extreme precipitation will increase. Estimates range from an increase of 11-40% by 2049 and 18-55% by 2099 (Das, 2011).
- Water temperature
  - Along the entire western slope of the Sierra Nevada at elevations ranging from 500-2500 m, climate warming is projected to warm stream temperatures approximately 1.6 ^{o}C for every 2 ^{o}C rise in average annual air temperature. Stream temperatures warmed the most during spring. Between wet and dry years, stream temperatures reach similar maxima but, warm water conditions (greater than 18 ^{o}C) persisted for 1-2 months during wet years and increased to 3-4 months during dry years. Streams in the central to north portion of the Sierra Nevada appear to be more susceptible to increases in the average annual number of weeks stream temperatures exceed 21 ^{o}C; the watersheds of the southern Sierra Nevada appear to be less vulnerable to changes in thermal regimes (Null, 2012).
- Storm frequency and intensity
  - Warmer temperatures may cause a greater number of extreme convective storms, including enhanced occurrence of lightning strikes (Hallett, 2010).

5. Non-climate Related Threats

- Residential and commercial development
  - The conversion of forested lands to residential or commercial developments has been one of the most destructive things experienced by Sierra Nevada meadows. Meadows and rivers are considered prime locations for human settlements. These developments often destroy meadows. Because of this, meadows and riparian lands are often on private lands. Hardened surfaces can reduce the amount of groundwater recharge, altering the hydrology and likely reducing the water availability of downstream meadows.
- Agriculture and aquaculture
  - Livestock grazing in the meadows of the Sierra Nevada has occurred for more than 100 years. Prior to the introduction of livestock, moderate to light grazing was done by native animals like deer, bighorn sheep and small mammals. Historic grazing in meadows is thought to be a cause of widespread meadow deterioration (Ratliff, 1985). Grazing causes permanent changes to features of meadows such as compacting of soil, increase in erosion, and channel incision.
  - Subalpine meadows experienced extensive degradation in the late 1800s due to cattle grazing. The livestock trampling broke down the soil, allowing streams and erosion to occur, which lowered the water table. Meadow vegetation will only return where the water table is restored to its natural height or, near the surface (Odion). 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 2,200-2,700 m, cattle use was negatively correlated to meadow wetness (Roche, 2012).
- Energy production and mining
- Transportation and service corridors
  - Roads or trails are commonly installed near or in meadows because meadows commonly form in the flatlands of valleys. The construction of roads can cause localized compaction of soil which reduces water holding capacity and infiltration. The disturbance of construction can introduce non-native species. Once installed, roads nearby or adjacent to meadows increase surface runoff which can increase localized erosion.
- Biological resource use
- Altered interspecific interactions
  - Changes in meadow hydrology, fire regime or overgrazing can cause a grass and sedge dry meadow to convert to sagebrush scrub. Sagebrush will outcompete native meadow species unless both groundwater levels are restored and sagebrush is actively removed (Berlow, 2003). Fire can also help suppress sagebrush and enhance meadow regrowth.
  - Lodgepole pine is known to invade mountain meadows. The trees reduce the area of open meadow, alter light and moisture availability and alter species composition. Years with low snowpack and early snowmelt may favor lodgepole pine seedling establishment (Ratliff, 1985). Out of 101 meadows in six National Forests in the Sierra Nevada and Southern Cascade ranges, 27% had little to no

conifer cover while 40% had conifer cover greater than 10%, 12% of the meadows had conifer cover greater than 20% (Living Assessment, 2013).

- Human intrusions and disturbance
  - Channel incision, gullying, or other modifications to a meadow's hydrology can be highly destructive. These features can alter the groundwater level in meadows, the rate of water transport away from meadows and alter seasonal overflow patterns. Out of 101 meadows in six National Forests in the Sierra Nevada and Southern Cascade ranges, 46% of riparian meadows were not significantly incised while 54% were. (Living Assessment, 2013)
  - Hikers on recreational trails can serve as a vector for invasive or non-native species.
  - Trails and campsites can fragment meadows.
  - Off-roading vehicles have damaged meadows due to soil compaction.
- Natural system modification
  - Destruction of the surrounding forest and shrub cover can reduce the amount of precipitation that infiltrates to the groundwater that feeds meadows.
  - Peat soil meadows require the buildup of soils with high organic matter and moisture; they take hundreds to thousands of years to develop by can be lost through drying and oxidation in years to decades (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, 2004).
- Pollution and poisons
- Geological events
  - Meadows tend to form where a small basin or wide valley fills with a shallow layer of soil.

6. Other Sensitivities

- Management

Adaptive Capacity

1. Habitat Extend and Characteristics

- Geographic extent in California
  - Meadows occupy roughly 10% of the Sierra Nevada. They have historically been classified as "wet, moist or dry" meadows but can also be classified based upon their elevation- montane (mid-altitudinal), and subalpine and alpine (high altitude). (Ratliff, 1985).

2. Landscape Permeability

- Barriers to dispersal or fragmentation

3. Habitat Diversity and Community Structure

- Diversity of component species
  - Trees are colonizing historically subalpine meadows. (Millar, 2004) A warming climate may dry out existing meadows and riparian lands, allowing greater conifer and deciduous tree species recruitment and growth. Willow and cottonwood recruitment may be impaired due to changes in hydrology.
- Community structure
  - A summary for meadow condition of low and middle gradient riparian meadow areas in the Sierra Nevada was developed. High condition sites were in good health and had a high proportion of late successional plant species, deeper root depths and little bare ground. Sites in low condition had a low proportion of late successional plants, shallow roots, and a high percent of bare ground. (Stillwater Sciences, 2012)

Region	Low	Moderate	Upper Moderate	High
North	4	47	40	18
Central	14	52	42	16
South	9	69	61	34

Exposure

Predictions for changes associated with climate change for the Sierra Nevada include reduced snowpack and earlier, more rapid spring snowmelt (Siegel et al. 2008). Reduced magnitude of spring flood on snowmelt rivers in western North America may dramatically alter riparian plant communities by stabilizing channels, reducing the fluvial disturbance that drives patch dynamics, and reducing hydrologic connectivity between the channel and the floodplain (Perry et al. 2012). Reduced summer base flow may increase the frequency or duration of zero-flow periods, or lower water tables and reduce riparian wetland inundation (Seavy et al. 2009). Long-term reduction in sediment transport and deposition and rates of channel migration and abandonment may shrink the areas where pioneer species establish (Perry et al. 2012). According to Null et al. (2010) models, the American, Yuba, Bear, Mokelumne and Cosumne Rivers in the northern Sierra Nevada, may experience the most altered aquatic and riparian ecosystems under climate projections, suggesting that this sub-region may have greater flow reductions than surrounding watersheds (Null et al 2010).

Increased CO_2, together with warming, may alter photosynthetic rates and plant tissue chemistry (Perry et al. 2012). Increase air and surface water temperatures in riparian areas may lead to increased heat stress, altering phenology and disrupting specialized biotic interactions by inducing northward, upward and upstream shifts in geographic distribution (Seavy et al. 2009, Perry et al. 2012). Plants in western North America that are limited by cold temperatures and favored by low precipitation may spread northward and to higher elevations. Conversely, species that are limited by warm temperatures may decline in the south and at low elevations. Ecotypic variation in cold or heat tolerance may lead to incremental northward or upward migration by populations adapted to warmer temperatures (Perry et al. 2012).

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 (Perry et al. 2012).

Subalpine meadows in the Sierra Nevada experienced episodic invasion of pine in 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).

Salt cedar/tamarisk (*Tamarix ramosissima*), a widespread invasive alien tree along streams in the southwestern US, is replacing southwestern riparian habitats dominated by native cottonwoods (*Populus spp*.) and willows (*Salix spp*.) (Finch et al. 2012). Tamarisks consume more water than do native riparian species, using an additional 1.4-3.0 billion cubic meters of water each year (Pejchar and Mooney 2009). In addition, tamarisk (*Tamarix spp*.) showed no evidence of temperature constraints in its distribution, and was not shown to be influenced by the direct effects of climate change in its spread in riparian areas (Friggins et al. 2012). Tamarisk also rebounds more quickly after fire than native species in the southwestern US (Bradley et al. 2009, Finch et al. 2012), and like yellow star-thistle (*Centaurea solstitialis)*, there is little potential for restoration of invaded areas (Bradley et al. 2009).

Lower base flows in monsoon rivers may have effects similar to, but more pronounced than, those in snow-melt rivers, including declines in drought-intolerant cottonwoods (*Populus spp.*), willow (*Salix spp.*), and perennial herbs, increases in drought tolerant species and annuals, declines in canopy height and cover (due to changes in species composition) and narrowing of mesic riparian zone. Some reaches may shift from perennial to intermittent flow, potentially favoring introduced species tolerant of intermittent flow (e.g. tamarisk), and obligate wetland species may disappear (Perry et al. 2012).

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). Because riparian areas have higher water content than surrounding upland areas, they absorb heat and buffer organisms against extreme temperatures (see: Naiman et al. 2000). During previous periods of climate change, riparian areas served as refugia because they provided microclimates that protected plant biodiversity and provided for animals with thermoregulatory limitations (Seavy et al. 2009). These landscape features tend to co-occur in the interior mountain ranges, leaving the Central Valley and interior deserts with the highest potential exposure to climate-induced change (Klausmeyer et al. 2011).

Aspen (*Populus termuloides*)

Aspen exist under an extremely broad range of temperatures in North America (Rehfeldt et al. 2009). For the latter half of the 20th century, aspen has been in a period of decline, thought to be the result of fire suppression, which allowed succession to result in assemblages that do not include aspen (Rehfeldt et al. 2009). All the general climate models run by Rehfeldt et al. (2009) describe aspen eventually shifting toward higher elevations. As conditions warm and dry in the Sierra Nevada, Rogers et al. (2007) expect an expansion of aspen stands associated with increased fires (Rogers et al. 2007). Simulations by Krawchuk and Cummings (2011) of increased wildfire to distant future (2080-2089) conditions similarly generated a rise in abundance of relatively inflammable aspen-dominated forests. However, Morelli and Carr (2011) suggest that while increase in frequency of physical disturbances (e.g., floods and wildlife) alone would be expected to increase wildfire, interactions between different factors make the net effect of extreme weather on aspen difficult to predict. While snow cover may provide insulation for roots in extreme cold, and inhibit ungulate browsing, an analysis by Brown et al. (2006) of aspen extent in the western US showed mild winters and warmer, wetter summers favored aspen (Morelli and Carr 2011). Aspen in southwestern Colorado were found to differentially reproduce sexually or asexual in response to climatic variation. Seedling (sexual) establishment was correlated with summers with cooler average maximum temperatures (21 to 22˚C) and wetter springs (5 to 6 cm), while asexual reproduction was correlated with drier springs (3 to 4cm) and summers with warmer average max temperatures (23 to 24˚C) (Morelli and Carr 2011).

A study by Classen et al. (2010) suggests that early successional woody species that have seeds with spring-maturing early phenology (e.g., *Populus spp*.) may be more susceptible to climate change than seeds with fall-maturing late phenology (Classen et al. 2010). Aspen in Alberta, Canada that responded to warming temperatures between 1953-2006 by advancing flowering dates by approximately two weeks, shifted their bloom period closer to receding winter, thus putting them at danger of damage from late-spring frost (Beaubien and Hamann 2011).

Aspen growth at seven out of ten sites displayed significant negative correlation with temperature, indicating that warm temperatures generally inhibit growth in northwest Colorado and southern Wyoming. Aspen growth in this area was less associated with precipitation (Hanna and Kulakowski 2012). Conversely, mortality, such as evidenced in sudden aspen decline (SAD) in the intermountain West, appears to have a strong climate correlation, and most occurrences can be related to high temperatures and drought (Morelli and Carr 2011). Drought may also reduce sprouting after a disturbance because of higher susceptibility to insects and pathogens (Morelli and Carr 2011). This finding is supported by a study in Utah suggesting that incremental temperature increases in the next century will facilitate widespread introductions of gypsy moth into previously temperature-limited elevation zones containing hardwoods with no previous exposure to gypsy moth, which may lead to the destruction of large stands of quaking aspen, bigtooth maple and Gambel oak (Shepperd et al. 2006).

Alternatively, aspen distribution may simply shift if migration and regeneration or seedling establishment rates are sufficient to adapt to environmental change (see: Iverson et al. 2004) (Morelli and Carr 2011)

In the Rocky Mountains, the lower elevation at which climate supports quaking aspen (*Populus tremuloides*) is expected to increase by 250m by 2030, and 750 meters by 2090 (Sturrock et al. 2011).

Willow (*Salix spp*.)

Greater water stress in the arid and semiarid western North America will favor drought-tolerant species and reduce abundance of dominant, drought-intolerant cottonwoods and willows (Perry et al. 2012).

<u>Animals</u>

In riparian systems of western US, reduced precipitation, early and reduced snowmelt, and higher temperatures will alter the timing and magnitude of stream flow, resulting in decreases in vegetation cover and in species requiring moist soil conditions. In turn, this will lead to declines in the diverse animal species dependent on the riparian zone for reproduction and survival, and will have cascading impacts to the adjacent terrestrial ecosystem (Yarnell et al. 2010, Finch et al. 2012). In North America, arthropods, aquatic mammals and waterfowl are highly dependent upon availability and quality of aquatic habitats for successful breeding, and in the case of waterfowl, nesting (Wrona et al. 2006, Yarnell et al. 2010). Bats in the Colorado front-range experience lower reproductive rates during warm and dry years with low streamflow (Perry et al. 2012).

Warmer streamwater and intermittent flows may reduce abundance of some aquatic insects, which as adults are important riparian prey (Perry et al. 2012). Reduced inundation may increase small mammal populations in riparian areas, increasing herbivory and bird nest predation, as mammalian predators remain closer to rivers during dry periods and gain access to riverine islands (Perry et al. 2012). In western deserts, warming may promote wintertime and springtime activity, and increase the time that herbivores or predators spend browsing or hunting in the shade of riparian vegetation (Perry et al. 2012). Conversely, increased CO_2 may reduce consumption by insects that rely on CO_2 gradients to locate fruit, flowers, prey, or ovipositioning sites (Perry et al. 2012).

Further loss, degradation, and fragmentation of riparian areas, particularly riparian woodlands, 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). Northward colonization by southern species will likely result in competitive exclusion of "northern" species for habitat and resources (Wrona et al. 2006), and increased movements of wildlife populations seeking to adapt may increase conflicts with humans in recreational areas (Finch et al. 2012).

Birds

Given that the vast majority of western bird species depend on deciduous riparian systems, loss or even reduction of the deciduous component is a major concern for the maintenance of biodiversity. According to an analysis by Gardali et al. (2012), bird taxa in grassland and oak woodland habitats are the least vulnerable to climate change in California, and wetland bird taxa are the most vulnerable (Gardali et al. 2012). In riparian areas in the semi-arid western North America, decreases in mature cottonwood (*Populus* section *Aigeiros*) and lower plant structural diversity due to reduced flooding and associated geomorphic changes may particularly affect canopy and tall-shrub foraging and nesting guilds. Decreases in preferred nest trees may consequently increase nest predation. Advances in plant springtime phenology may reduce food and refuge quality for Neotropical migratory birds that stop in riparian habitats en route to northern breeding areas (Perry et al. 2012). 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). Documentation of local extinction of bird species associated with the decline in deciduous plants in 22 snowmelt drainages on the Mogollon Rim in central Arizona emphasized the potential seriousness of climate responses in mountain and riparian habitats. Reduced snowpack in the Sierra Nevada, together with earlier, more rapid snowmelt could have substantial effects on meadow-nesting birds (Siegel et al. 2008).

Great gray owl (*Strix nebulosa*)

The great gray owl is considered vulnerable to climate change (Gardali et al. 2012).

Willow Flycatcher (*Empidonax traillii extimus)*

According to Gardali et al. (2012) the willow flycatcher is one of eight threatened or endangered bird species in California considered not vulnerable to climate change (Gardali et al. 2012). However, meadow desiccation appears to be the most important proximate factor in willow flycatcher decline in the Sierra Nevada (Green et al. 2003). Drier meadows result in reduction of willow cover and standing water leading to encroachment by conifers. Presence of conifers and lack of standing water may allow predators easier access to nests, leading to a principle cause in willow flycatcher population decline in the Sierra Nevada (Green et al. 2003).

Sigel et al. (2008) postulate that the extirpation of the willow flycatcher from meadows in Yosemite National Park may be in response to climate cycles leading to meadows drying out. Once willow patches in the Sierra Nevada are degraded, whether due to climate change or other anthropogenic cause, the ability of these patches to support nesting flycatchers is lost, and the birds do not have the plasticity to nest in other habitat types (Green et al. 2003). Moreover, events that influence the overall abundance of arthropods, such as regional droughts, may be critical drivers of productivity for generalists such as willow flycatchers (Durst et al. 2008).

Amphibians

Amphibian and arthropod species may be especially vulnerable to climate change because of their sensitivity to reduced surface water, aquatic habitat and habitat connectivity (Finch et al. 2012, Perry et al. 2012). Despite increased flooding, climate change will exacerbate summer drought, reduce streamflow, and produce drier conditions in riparian areas, making riparian and flood-plain habitat less hospitable for amphibian species, such as Pacific chorus frog (*Pseudacric regilla*) western toad (*Bufo boreas*), and red-legged frog (*Rana aurora*) (Hass et al. 2011). Extinctions of amphibian species in montane regions in Colorado is attributed to drought conditions experienced during the mid 1970s (Finch et al. 2012). Under future climate scenarios, drought conditions are projected to increase in frequency, severity, and spatial extent, with potentially large declines in amphibian populations (Finch et al. 2012).

Whether species can shift their range in response to drying may be determined as much by the ability of a species to persist during short periods of unfavorable climate, as their ability to disperse (Early and Sax 2011). Fluctuations in the directional trend of climate change can create climate gaps, which prevent species from reaching climatically suitable regions, even in the absence of physical barriers. Gaps can arise if a portion of a climate path is available at a time in which a species is unable to pass through it. Early and Sax (2011) predict that climate gaps will cause many amphibian species to become endangered, even though they are projected to have large areas of suitable climate space in 2100. In addition, warming may increase temperature-dependent metabolic rates in ectotherms, and thus increase their energy demands and consumption (Perry et al. 2012).

Davidson et al. (2001, 2002) conclude that climate change, including precipitation effects, is not a primary cause of amphibian decline in California. In their study, only the western spadefoot toad (*Spea hammondii)* had both significantly greater declines in the south and at lower elevations, as predicted under the climate change hypothesis. Despite this, declines for the western spadefoot toad appear to be more related to habitat degradation. The spatial pattern of declines for the foothill yellow-legged frog (*Rana boylii)* was the most suggestive of climate change influence, with increasing declines to the south and at drier sites (Davidson et al. 2002). In contrast, they suggest that habitat destruction and wind-borne agrochemicals play primary roles, recognizing that the untested factors of disease and introduced species may play a role.

Parasites on amphibians

Amphibians are also vulnerable to indirect climate impacts. Nonlinear relationships between temperature and infection are likely to be common in amphibians in North America. Some amphibian species (e.g., Pacific tree frog) experience increases in tadpole development with warming temperatures, with decreased time to metamorphosis and increased length and mass at metamorphosis. However, the prevalence of severe limb deformities also increased significantly as temperature increased from 20C to 26C. Similarly, warming temperatures increased a parasite's (*Ribeiroia ondatrae*) ability to penetrate the Pacific treefrog tadpole host, but reduced the parasite's ability to survive outside and establish inside hosts. Accelerated larval development of the Pacific tree frog may have reduced the period in which hosts are highly sensitive to infection (Paull et al. 2012)

In addition, outbreaks of a pathogenic copepod (*Lernaea cyprinacea*) in Northern California are more severe following unusually warm summers (see: Kupferberg et al. 2009). Reduced water levels may force amphibian larvae into high densities, and reduced discharge may slow river velocities, which could allow easier transition of the parasite (Blaustein et al. 2010). Moreover, chytridiomycosis, an emerging infectious disease, caused by a fungal pathogen, is having a devastating impact on native frogs of the Sierra Nevada, already weakened by the effects of pollution and introduced predators (Wake and Vredenburb 2008).

Fire response

No clear pattern exists regarding effects of wildfire on amphibians, possibly because there are limited studies for most species. Response to fire varies according to life history strategy. According to a meta-analysis conducted by Hossak and Pilliod (2011), of 19 populations in Western US, studied before and after fire, 7 displayed negative response to fire, 5 positive, and 6 displayed no response to fire.

Because of their life history, species that breed in small, cold streams, and lungless salamanders may take longer to recover from wildfire than species that breed in standing or slow, warm streams. Positive responses after wildfire were evidenced for the western toad (*Anaxyrus boreas*) and the arroyo toad (*Anaxyrus californicus*), which is consistent with the affinity of some toads for disturbed habitat (Hossak and Pilliod 2011). Fire effects were greater in forests where fire had been suppressed and in areas that burned with high severity. Species that breed in streams were also vulnerable to post-fire habitat changes, especially in the Southwest. Pools may dry or fill with sediment, and post-fire debris flows may greatly reduce rearing habitat. In contrast to fishes, amphibian re-colonization from adjacent areas is expected to occur slowly (Hossak and Pilliod 2011).

Foothill yellow-legged frog *(Rana boylii)*

If the predicted effects of climate change on Sierra Nevada water balance prove correct and the winter snowpack diminishes, the summer drying of small lakes is likely to become more frequent, and Sierra Nevada yellow-legged frog recruitment less successful. Of additional concern is that the decline of high-snowpack years may also depress egg production, as the highest egg mass counts have been recorded in summers following the high-snowpack years. Thus, climate change is likely to result in a lower breeding success from the combination of drying induced mortality (lower recruitment) and the loss of the high egg production that is dependent on above-average snowpack (lower fecundity) (Lacan et al. 2008).

Yosemite toad (*Anaxyrus canorus* = *Bufo canorus*)

No information found

Primary sources

Beaubien, E., & Hamann, A. (2011). Spring Flowering Response to Climate Change between 1936 and 2006 in Alberta, Canada. BioScience, 61(7), 514-524.

Berlow, E.L., C.M. D'Antonio, H. Swartz. 2003. Response of herbs to shrub removal across natural and experimental variation in soil moisture. *Ecological Applications*. 13: 1375-1387.

Blaustein, A. R., Walls, S. C., Bancroft, B. A., Lawler, J. J., Searle, C. L., & Gervasi, S. S. (2010). Direct and indirect effects of climate change on amphibian populations. Diversity, 2(2), 281-313.

Bradley, B. A., Oppenheimer, M., & Wilcove, D. S. (2009). Climate change and plant invasions: restoration opportunities ahead? Global Change Biology, 15, 1511-1521.

Classen, A. T., Norby, R. J., Campany, C. E., Sides, K. E., & Weltzin, J. F. (2010). Climate Change Alters Seedling Emergence and Establishment in an Old-Field Ecosystem. PLoS ONE, 5(10), e13476.

D'Antonio, C.M., E.L. Berlow, K.A. Haubensak. 2004. Invasive exotic plant species in Sierra Nevada ecosystems.

Das, T. M.D. Dettinger, D.R. Cayan, H.G. Hidalgo. 2011. Potential increase in floods in California's Sierra Nevada under future climate projections. *Climatic Change*. 109: S71-S94

Davidson, C., Shaffer, H. B. & Jennings, M. R. (2001). Declines of the California red-legged frog: Climate, UV-B, habitat, and pesticides hypotheses. Ecological Applications, 11(2), 464 – 479.

Davidson, C., Shaffer, H. B. & Jennings, M. R. (2002). Spatial tests of the pesticide drift, habitat destruction, UV-B, and climate-change hypotheses for California amphibian declines. Conservation Biology, 16(6), 588 – 1601.

Durst, S. L., Theimer, T. C., Paxton, E. H. & Sogge, M. K. (2008). Age, habitat, and yearly variation in the diet of a generalist insectivore, the southwestern willow flycatcher. The Condor, 110(3), 514 – 525.

Early, R. & Sax, D.F. (2011). Analysis of climate paths reveals potential limitations on species range shifts. Ecology Letters, 14, 1125-1133.

Finch, D. M., Smith, D. M., LeDee, O., Cartron, J.-L. E. & Rumble, M. A. (2012). Climate change, animal species, and habitats: Adaptation and issues. In, Finch, Deborah M., ed. 2012. Climate change in grasslands, shrublands, and deserts of the interior American West: a review and needs assessment. General Technical Report RMRS-GTR-285. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station

Friggins, M. M., Warwell, M. V., Chambers, J. C. & Kitchen, S. G. (2012). Modeling and predicting vegetation response of western USA grasslands, shrublands, and deserts to climate change. In, Finch, Deborah M., ed. Climate change in grasslands, shrublands, and deserts of the interior American West: a review and needs assessment. General Technical Report RMRS-GTR-285. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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

Green, G. A., Bombay, H. L. & Morrison, M. L. (2003). Conservation assessment of the willow flycatcher in the Sierra Nevada. Sacramento, CA: US Forest Service Region 5. 63pp.

Haas, S. E., Hooten, M. B., Rizzo, D. M. & Meentemeyer, R. K. (2011). Forest species diversity reduces disease risk in generalist plant pathogen invasion. Ecology Letters, 14, 1108 – 1116.

Hallett, D.J., R.S. Anderson. 2010. Paleofire reconstruction for high-elevation forests in the Sierra Nevada, California with implications for wildfire synchrony and climate variability in the late Holocene. *Quaternary Research*. 73: 180-190.

Hanna, P. & Kulakowski, D. (2012). The influences of climate on aspen dieback. Forest Ecology and Management, 274, 91 – 98.

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

Hossack, B. R. & Pilliod, D. S. (2011). Amphibian responses to wildfire in the western United States: Emerging patterns from short-term studies. Fire Ecology, 7(2), 129 – 144.

Houlton, B. Z., & Field, C. B. (2010). Nutrient limitations of carbon uptake: From leaves to landscapes in a California rangeland system. Rangeland Ecology & Management, 63, 120-127.

Klausmeyer, K. R., Shaw, M. R., MacKenzie, J. B. & Cameron, D. R. (2011). Landscape-scale indicators of biodiversity's vulnerability to climate change. Ecosphere, 2(8), 1 - 18.

Krawchuk, M. A. & Cumming, S. G. (2011). Effects of biotic feedback and harvest management on boreal forest fire under climate change. Ecological Applications, 21 (1), 122 – 136.

Lacan, I., Matthews, K. & Feldman, K. (2008) Interaction of an introduced predator with future effects of climate change in the recruitment dynamics of the imperiled Sierra Nevada yellow-legged frog (Rana sierra). Herpetological Conservation and Biology, 3 (2), 211 – 223.

Living Assessment. 2013. Chapter 1 Bio-region: Sierra Nevada bio-region. Avail at http://livingassessment.wikispaces.com/Chapter+1+Bio-region#Riparian Ecosystems: Current Condition. Accessed on Feb.28 2013.

Micheli, E.R., 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: 687-697.

Millar, C. I., Westfall, R. D., Delany, D. L., King, J. C. & Graumlich, L. J. (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.

Morelli, T. L. & Carr, S. C. (2011). A review of the potential effects of climate change on quaking aspen (Populus tremuloides) in the Western United States and a new tool for surveying sudden aspen decline. General Technical Report PSW-GTR-235. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 31 p.

Null, S. E., Viers, J. H. & Mount, J. F. (2010). Hydrologic response and watershed sensitivity to climate warming in California's Sierra Nevada. PLoS ONE, 5(4), 1-16.

Null, S.E., J.H. Viers, M.L. Deas, S.K. Tanaka, J.F. Mount. 2012. Stream temperature sensitivity to climate warming in California's Sierra Nevada: impacts to coldwater habitat. *Climate Change*.

Odion, DC, TL, Dudley, CM D'Antonio. Cattle Grazing in Southeastern Sierran Meadows: Ecosystem Change and Prospects for Recovery.

Paull, S. H., Lafonte, B. E. & Johnson, P. T. (2012). Temperature-driven shifts in a host-parasite interaction drive nonlinear changes in disease risk. Global Change Biology, 18, 3558 – 3567.

Pejchar, L., & Mooney, H. A. (2009). Invasive species, ecosystem services and human well-being. Trends in Ecology and Evolution, 497-504.

Perry, L. G., Anderson, D. C., Reynolds, L. V., Nelson, S. M., & Shafroth, P. B. (2012). Vulnerability of riparian ecosystems to elevated CO_2 and climate change in arid and semiarid western North America. Global Change Biology, 18, 821 - 842.

Ratliff, R.D. 1985. Meadows in the Sierra Nevada of California: state of knowledge.

Rehfeldt, G. E., Ferguson, D. E. & Crookston, N. L. (2009). Aspen, climate and sudden decline in western USA. Forest Ecology and Management, 258, 2353 – 2364.

Roche, LM, AM Latimer, DJ Eastburn, KW Tate. 2012. Cattle Grazing and Conservation of a Meadow-dependent Amphibian Species in the Sierra Nevada. Plos one.

Rogers, P. C., Shepperd, W. D. & Bartos, D. L. (2007). Aspen in the Sierra Nevada: Regional conservation of a continental species. Natural Areas Journal, 27 (2), 183 – 193.

Safford, H.D., M. North, M.D. Meyer. Chapter 3: Climate change and the relevance of historical forest conditions. In Managing Sierra Nevada Forests.

Seavey, N. E., Gardali, T., Golet, G. H., Griggs, F. T., Howell, C. A., Kelsey, R., Small, S. L., Viers, J.H & Weigand, J. F. (2009). Why climate change makes riparian restoration more important than ever: recommendations for practice and research. Ecological Restoration, 27(3), 330-338.

Shepperd, W. D., Rogers, P. C., Burton, D. & Bartos, D. L. (2006). Ecology, biodiversity, management, and restoration of aspen in the Sierra Nevada. General Technical Report RMRS-GTR-178. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station 122 p.

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

Stillwater Sciences. 2012. A guide for restoring functionality to mountain meadows of the Sierra Nevada. Prepared by Stillwater Sciences, Berkeley, California for American Rivers, Nevada City, California.

Sturrock, R. N., Frankel, S. J., Brown, A. V., Hennon, P. E., Kliejunas, J. T., Lewis, K. J., … Woods, A. J. (2011). Climate change and forest diseases. Plant Pathology, 60, 133-149.

Wake, D. B. & Vredenburg. (2008). Are we in the midst of the sixth mass extinction? A view from the world of amphibians. Proceedings of the National Academy of Science, 105 (Suppl 1), 11466-11473.

Wrona, F. J., Prowse, T. D., Reist, J. D., Hobbie, J. E., Levesque, L., & Vincent, W. F. (2006). Climate change effects on aquatic biota, ecosystem structure and function. Ambio, 359-369.

Yarnell, S. M., Viers, J. H. & Mount, J. F. (2010). Ecology and management of the spring snowmelt recession. BioScience, 60(2), 114 – 127.

Secondary sources

Kupferberg, S.J.; Catenazzi, A.; Lunde, K.; Lind, A.J.; Palen, W.J. (2009). Parasitic Copepod (*Lernaea cyprinacea*) Outbreaks in Foothill Yellow-legged Frogs (*Rana boylii*) Linked to Unusually Warm Summers and Amphibian Malformations in Northern California. Copeia. 1, 529-537.

Brown, K.; Hansen, A.J.; Keane, R.K.; Graumlich, L.J. 2006. Complex interactions shaping aspen dynamics in the greater Yellowstone ecosystem. Landscape Ecology. 21: 933–951.

Naiman, R.J., R.E. Bilby and P.A. Bisson. (2000). Riparian ecology and management in the Pacific coastal rain forest. Bioscience 50:996–1011.