A guide to climate-smart meadow restoration in the Sierra Nevada and southern Cascades

Version 1.0, May 2019

Marian E. Vernon, Brent R. Campos, and Ryan D. Burnett

Point Blue Contribution Number 2232

Point Blue

Conservation science for a healthy planet

3820 Cypress Drive, #11 Petaluma, CA 94954
T 707.781.2555 | F 707.765.1685
pointblue.org

Table of Contents

Point Blue Conservation Science – Point Blue's 160 staff and seasonal scientists conserve birds, other wildlife and their ecosystems through scientific research and outreach. At the core of our work is ecosystem science, studying birds and other indicators of nature's health. Visit Point Blue on the web www.pointblue.org.

Cover photo: *Beaver Dam Analog at Childs Meadow. Photo by Ryan D. Burnett.*

Introduction

This handbook provides restoration practitioners with guidance to incorporate climate change considerations into the planning and design of Sierra Nevada meadow restoration projects. Implementation of the recommended approaches and best management practices in this handbook can help practitioners increase the probability that restored meadows are resilient to the consequences of climate change.

Sierra Nevada meadows are a rare and critically important component of California's Sierra Nevada ecosystem, the value of which far outweighs the 2% of the system they occupy. Meadows provide vital ecological functions, including carbon storage, groundwater recharge, flood attenuation, water quality improvement, and habitat for a diversity of species, including many of conservation concern. However, 40-60% of meadows are degraded as a result of past and current land uses and hence are in urgent need of conservation action to restore their important ecological services for the benefit of human and natural communities (Drew et al. 2016).

The Sierra Meadows Partnership (SMP) was formed in 2016 to address this widespread meadow degradation, setting the goal of restoring and protecting 30,000 acres of Sierra meadows by 2030 to enhance water, carbon, and biodiversity benefits. The SMP's strategy and goal reflects that of numerous state and federal agencies and organizations that also recognize the importance of restoring Sierra meadows as a conservation priority (e.g., National Fish and Wildlife Foundation 2010; California Natural Resources Agency et al. 2014; USDA Forest Service 2015; Watershed Improvement Program 2016).

Efforts to restore Sierra meadows are being implemented in the context of a rapidly changing climate, which poses challenges to achieving the SMP's goal. Traditional restoration approaches use a baseline of historic conditions and the historic range of variability as a reference for restoration outcomes. However, climate change is likely to lead to future conditions and variability unlike that observed in the past (Addington et al. 2018). The Sierra Nevada and southern Cascades region is already experiencing the effects of climate change, most notably declining snowpack (Reich et al. 2018; Mote et al. 2005). Because these impacts are already occurring, it is necessary to understand the range of projections for this region and begin integrating this information into restoration projects to ensure they are successful under a range of projected conditions as our climate continues to change. Restoring Sierra meadows in reference to a historic baseline is unlikely to ensure that the restored meadow will be resilient, which we define as the capacity of an ecosystem to return to desired conditions and regain basic characteristics and functions after disturbance (Stein et al. 2014; Aslan et al. 2018).

In order to retain our investment in meadow restoration, it is necessary to design and implement climate-smart meadow restoration projects in the context of a changing climate and associated uncertainty about future conditions (Veloz et al. 2013). We recommend that practitioners engage in climate-smart ecological restoration, which we define as the process of enhancing ecological function of degraded, damaged, or destroyed areas in a manner that makes them resilient to the consequences of climate change. The purpose of this handbook is to demonstrate how climate change considerations can be integrated into planning and design for Sierra meadow restoration projects and provide recommendations of best management practices to ensure restored meadows are resilient to climate change. Our approach combines a traditional climate change vulnerability assessment with Point Blue's climate-smart restoration principles to describe both the potential vulnerabilities that climate change poses to achieving restoration goals as well as specific restoration and management actions that can help address and reduce identified vulnerabilities.

Handbook Outline

This handbook is divided into three main sections. In Section I, we introduce the concept of climate vulnerability and describe the four steps of a climate vulnerability assessment process that can be used to identify how desired meadow restoration outcomes may be vulnerable to climate change impacts. This section includes a list of desired meadow restoration outcomes, an overview of climate projections for the Sierra Nevada region, and Point Blue's climate-smart restoration principles that can be used to design actions to address climate vulnerabilities. In Section II, we demonstrate how these concepts and principles can be applied by summarizing the results of a climate vulnerability assessment for four riparian meadow restoration projects in the northern Sierra and southern Cascades. This section includes a comprehensive list of climate vulnerabilities and suggested restoration actions associated with each desired restoration outcome. In Section III, we outline some additional climate-smart best management practices that practitioners can use to inform meadow restoration projects.

This handbook provides practitioners with two avenues by which they can integrate climate change considerations into their meadow restoration project. Practitioners can use Section I to learn how to conduct a vulnerability assessment process and apply climate-smart restoration principles to design actions to address climate vulnerabilities. Alternatively, or additionally, practitioners can use Section II to peruse already identified vulnerabilities and climate-smart restoration actions linked to comprehensive restoration outcomes (however, see below for appropriate geographies and hydrogeomorphic types). These already identified vulnerabilities and actions (which are summarized in Appendices B and C) can be directly integrated into meadow restoration designs. We do recommend becoming familiar with Section I even if starting with Section II is your chosen path. We also include a worksheet in Appendix A that practitioners can fill out for their own project.

The climate vulnerabilities and actions identified in Section II were developed through climate-smart restoration workshops hosted by Point Blue for four different riparian meadow restoration projects in the northern Sierra and southern Cascades. This region is lower in elevation and is projected to be more vulnerable to climate change when compared to the rest of the range (Viers et al. 2013; Rhoades et al. 2018). While the specific details of individual projects differed, the desired outcomes, vulnerabilities, and climate-smart actions identified by workshop participants were relatively consistent across projects. We feel confident that the vulnerabilities and climate-smart actions identified in Section II will prove useful in informing the design of riparian meadow restoration projects outside of the northern Sierra and in other meadow types. We do recommend, however, that practitioners working in higher elevation meadows in the central and southern Sierra and non-riparian meadow hydrogeomorphic types use Section I to conduct a vulnerability assessment for their own restoration project to ensure that vulnerabilities that may be specific to those particular locations and meadow types are not overlooked in restoration planning and design.

Section I: Conducting a climate vulnerability assessment

This section introduces a climate vulnerability assessment process that can be used to identify the potential vulnerabilities that climate change may pose to achieving desired outcomes for your meadow restoration project. Vulnerability is defined as the susceptibility of a system to a negative impact (Williams et al. 2008; Smit et al. 2000), and climate vulnerability assessments in particular are used to evaluate the degree to which a species, habitat, or ecosystem is susceptible to the adverse effects of climate change. The results of climate vulnerability assessments can be used to generate adaptation management actions to reduce vulnerabilities and increase the resilience of the species, habitat, or system of interest. Indeed, the purpose of conducting a vulnerability assessment is to help increase the likelihood that you can achieve your desired outcomes in the context of climate change and other stressors (Glick et al. 2011).

Climate vulnerability assessments include the following steps (after Glick et al. 2011), which are further described in this section:

1. Define objectives and desired outcomes
2. Gather relevant data
3. Assess climate vulnerabilities in the context of desired outcomes
4. Use results to identify climate-smart restoration actions and adaptation approaches

We encourage you to use the project planning worksheet in Appendix A to guide your own climate vulnerability assessment. The worksheet includes the four steps described in this section along with space for you to fill in results. The next section describes results from a climate vulnerability assessment specific to riparian meadows in the Sierra Nevada and southern Cascades region that can be used as a basis for a climate-smart meadow restoration design process.

Step 1: Define objectives and desired outcomes.

The first step of a vulnerability assessment is to define the objectives and desired outcomes of your restoration project (Glick et al. 2011). We define outcomes as a qualitative description of the desired end condition of the meadow after restoration. Each outcome should be linked to one or more specific, measurable objectives that can be used to assess whether desired outcomes have been reached. An example of an outcome for a meadow restoration project could be that the meadow supports diverse native meadow-dependent terrestrial and aquatic wildlife, including birds, amphibians, and fish. An associated objective for this outcome could be to increase willow cover to 30% of the meadow area to support willow flycatchers. Your outcomes and objectives can be used to assess whether the restoration project is successful and if any further restoration or management actions need to be implemented in order to move the system towards the desired state.

For the purposes of this handbook, we identified a comprehensive set of desired outcomes for restored meadows that can serve as a basis for identifying climate vulnerabilities and climate-smart actions. These desired outcomes were distilled from the meadow restoration objectives of our four climate-smart restoration workshops and from the Sierra Meadows Strategy (Drew et al. 2016), and are as follows:

- **Functional Meadow Hydrology.** The meadow exhibits hydrologic connectivity both laterally across the floodplain and vertically between surface and subsurface flows, contributing to groundwater recharge, late season stream flow, high water table, and attenuation and delay of peak flows.
- **Good Water Quality.** The meadow contributes to good water quality characterized by streams with low sediment outputs, low turbidity, and cool temperatures.
- **Healthy Meadow Soil.** The meadow features productive, healthy soil characterized by high levels of soil organic matter that have a high water holding capacity and net carbon sequestration.

- **Meadow Plant Species.** The meadow's hydrologic regime and forage utilization supports native meadow graminoid species and, where ecologically appropriate, riparian shrubs and trees of diverse age classes.
- **Meadow Wildlife.** The meadow supports diverse native terrestrial and aquatic wildlife, including birds, amphibians, and fish, that depend on meadows for some or all portions of their life cycle.
- **Resilience and Adaptive Capacity.** The meadow is resilient to and recovers from natural and human disturbances.

These outcomes were designed in the context of riparian meadow restoration projects, and as a result some may be less applicable to projects that seek to restore different meadow hydrogeomorphic types. Nevertheless, several outcomes are likely widely applicable across meadow restoration projects regardless of hydrogeomorphic type, such as meadow plant and wildlife species and healthy soil.

Step 2: Gather relevant data

The next step in a climate vulnerability assessment is to gather relevant data on climate projections for your project area. These projections will be the basis for identifying vulnerabilities to your desired restoration outcomes and climate-smart restoration actions. Here we summarize the range of climate change projections that the Sierra Nevada and southern Cascades region may experience by mid-century (2041-2060) and end of century (2081-2100). We first provide some initial context in regards to climate change modeling and then describe the resulting projections for the Sierra Nevada and southern Cascades region. These projections can inform your own climate vulnerability assessment; however, we encourage you to gather data about the specific climate projections for your project area when possible, which can help you develop a more targeted list of climate vulnerabilities and potential climate-smart restoration actions.

Climate scientists us four representative concentration pathways (RCPs) for climate modeling and research. These RCPs describe four possible climate futures, all of which are considered possible depending on how much greenhouse gas emissions are released in the years to come. These RCPs are also based on assumptions about future global socioeconomic conditions. The four RCPs (RCP2.6, RCP4.5, RCP6, and RCP8.5) are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values. Radiative forcing is the difference between the amount of sunlight absorbed by the atmosphere and the amount of sunlight radiated back into space; higher values indicate a stronger greenhouse effect.

Table 1 shows the global temperature projections under each RCP scenario for mid to late century. RCP8.5 represents the "business as usual" scenario, in which emissions continue to increase throughout the 21st century. RCP6.0 represents a stabilization scenario, with high greenhouse gas emissions rate that stabilizes after 2100. RCP4.5 represents a "mitigation" scenario, in which emissions are reduced; this scenario is loosely equivalent to that of what would be achieved if the world met the targets of the Paris Climate Accord (Reich et al. 2018). Finally, RCP2.6 represents a "peak" scenario, where emissions peak in mid-century and fall by 2100 to a radiative forcing value of 2.6. The projections for the Sierra Nevada described below are based on the assumption that we will continue along the "business as usual" scenario, although we do provide some information on how the projections differ for the "mitigation" scenario.

Table 1: Global temperature projections under each RCP scenario in degrees C.

	2046-2065	2081-2100
Scenario	Mean and *likely* range (in degrees C)	Mean and *likely* range (in degrees C)
RCP2.6	1.0 (0.4 to 1.6)	1.0 (0.3 to 1.7)
RCP4.5	1.4 (0.9 to 2.0)	1.8 (1.1 to 2.6)
RCP6.0	1.3 (0.8 to 1.8)	2.2 (1.4 to 3.1)
RCP8.5	2.0 (1.4 to 2.6)	3.7 (2.6 to 4.8)

The Sierra Nevada will experience greater temperature increases by mid and late century when compared to the rest of California. These rising temperatures are the main driver for hydrological changes that have implications for both the persistence of the Sierra's species and ecosystems as well as the availability of freshwater resources for human communities (Null et al. 2010; Viers et al. 2013; Reich et al. 2018). Under a business as usual scenario, the Sierra Nevada is projected to experience 4°F of warming by mid-century (2041-2060); under a mitigation scenario, this projection decreases to 3°F of warming (Reich et al. 2018). However, the degree of warming will vary across the range along elevational gradients. Under a business as usual scenario, low-elevation valleys and foothills are projected to experience temperature increases of 4°F at mid-century (2041-2060) and 5-7°F by late century (2081-2100) compared to a historic baseline of 1981-2000 (Reich et al. 2018). Middle elevations (5000-8000 feet) will experience the most warming as retreating snow cover exposes darker land surfaces that in turn absorb sunlight that would have been reflected by snowpack, leading to increased temperatures (Reich et al. 2018). The business as usual scenario projects 8-10°F of warming in the Sierra's mid-elevations by late century (2081-2100) when compared to the historic baseline of 1981-2010 (Reich et al 2018).

To put these warming trends into context, consider the following projections for Truckee, CA (elevation of 5,817 feet), which are representative of other mid-elevation locations in the Sierra. Under the business as usual scenario, the average annual mean maximum temperature for Truckee is projected to increase from the historic baseline of 59.8°F observed in 1981-2005 to 65°F at mid-century (2041-2060) and 69.2°F by late-century (2081-2100), representing average increases of 5.2°F and 9.4°F, respectively. The average annual minimum temperature is projected to increase from the historic baseline of 28°F observed in 1981-2005 to 32.1°F at mid-century (2041-2060) and 36.8°F at late-century (2081-2100), representing average increases of 4.1°F and 8.8°F, respectively. The number of extreme heat days per year for Truckee are also projected to increase. Extreme heat days are defined as those that exceed the 98th historical percentile of daily maximum/minimum temperatures based on observed historical data from 1961-1990 between April and October; for Truckee, this threshold value is 89.8°F. The number of extreme heat days per year for Truckee are projected to increase on average from 6 days/year in the historic baseline from 1981-2005 to 33 days/year by mid-century (2041-2060) and 66 days/year by late-century (2081-2100).

Warming temperatures will result in widespread hydrological changes throughout the Sierra, driven primarily by loss of snowpack and climatic water deficit (Stephenson 2007; Viers et al. 2013; Reich et al. 2018; Rhoades et al. 2018). Warming temperatures will cause more precipitation to fall as rain than snow, and these warmer temperatures and increased winter rainfall will cause snow to melt more

Sources of Climate Change Projections

If you are interested in exploring a more specific range of climate projections for the particular location of your project, the following are some resources that we recommend you consult:

Cal-Adapt: Cal-Adapt provides a view of how climate change might affect California. It features tools, data, and resources that can be used to conduct research, develop adaptation plans, and build applications. The available data can be queried to generate downscaled, high-resolution climate projections and graphics for your particular project area.

California Basin Characterization Model: The California BCM dataset provides historical and projected climate and hydrologic surfaces for the California hydrologic region, which encompasses the state of California and all the streams that flow into it. It simulates hydrologic responses to climate at the spatial resolution of a 270-m grid. The BCM's climate variables include precipitation, air temperature, April 1 snowpack, recharge, runoff, potential evapotranspiration, actual transpiration, and climatic water deficit (Flint et al. 2014).

quickly. By mid-century (2040-2069), under the business as usual scenario, snowpack is projected to decrease to 70% of average compared to the baseline period of 1981-2010; by late century (2081-2100), snowpack is projected to be just 36% of average compared to the same baseline (Reich et al. 2018). Under the mitigated scenario, snowpack is projected to be at 80% of average by mid-century and 70% of average by late-century (Reich et al. 2018). The most snow will be lost in mid-elevations as a result of albedo feedback, and snowpack is projected to disappear almost entirely at low elevations (below 5,000 feet) under the business as usual scenario (Reich et al. 2018).Snowpack declines are already being observed in the Sierra Nevada and other western mountain ranges (Figure 1). While some parts of the northern and southern Sierra have experienced some increases in April 1 snowpack in the past few decades, other parts of the Sierra have already experienced greater than 70% loss and extended drought in the most recent decade (post-2007) erased many of the formerly positive trends (Mote et al. 2018). The effects of warming temperatures on hydrology will also drive changes in the Sierra's biota. For example, Sierra-wide temperature-induced increases in potential evapotranspiration will alter the water balance to support plant species currently found at lower elevations (Stephenson 2007).

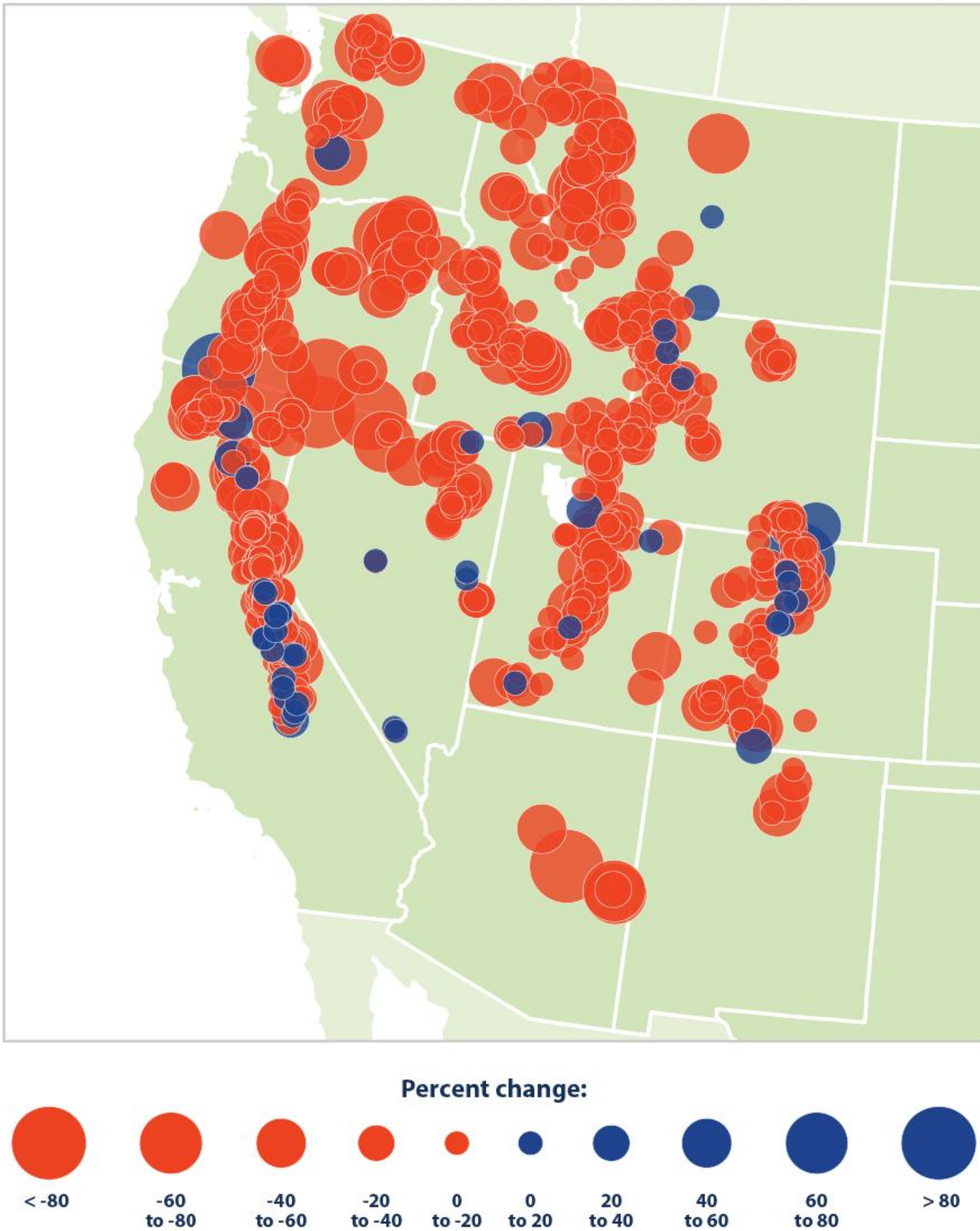

Figure 1: Trends in April snowpack in mountains of the western United States, 1955-2016. Data source: Mote, P.W. and D. Sharp 2016 update to data originally published in Mote et al. 2005. Retrieved from the U.S. EPA's "Climate Change Indicators in the United States," www.epa.gov/climate-indicators.

There is disagreement among climate models as to the direction and magnitude of change in precipitation in California and the Sierra Nevada, with some projecting increases and others projecting decreases. Nevertheless, there is agreement that there will be an increase in the amount of precipitation falling as rain instead of snow, which will result in a shift in the timing and amount of runoff towards earlier in the year (Viers et al. 2013; Garfin et al. 2013; Reich et al. 2018; Rhoades et al. 2018). There will likely be more precipitation-driven runoff in the winter and reduced snowmelt runoff in the spring (Viers et al. 2013). The centroid timing (also known as the runoff midpoint), which is defined as the point in time by which half of the total water that runs off in a given year has done so, will shift to earlier in the year (Viers et al. 2013; Reich et al. 2018). Under the business as usual scenario, the runoff midpoint is projected to occur 50 days earlier on average by late-century (2081-2100) compared to 1981-2000 (Reich et al. 2018). Under the mitigated scenario, the runoff midpoint is projected to occur 25 days earlier on average by late century compared to the historic baseline (Reich et al. 2018). The greatest shifts in runoff are projected to occur in mid-elevations of 5,000-8,000 feet (Reich et al. 2018). Shifts in the timing and amount of runoff will also result in longer periods of low-flow in the dry summer months (Viers et al. 2013). Although the northern latitudes are projected to experience a slight increase in precipitation, the greatest loss of peak water volume at peak timing will occur in the northern Sierra/southern Cascades at latitudes between 38.6°N to 42.4°N as a result in shifts in runoff driven by a shift from snowfall to rainfall and increased ablation leading to a reduced snowpack accumulation rate in this lower elevation region (Rhoades et al. 2018).

Table 2: Summary of temperature and hydrology projections for the Sierra Nevada under the business as usual and mitigation scenarios compared to historic baseline of 1981-2000 (after Reich et al. 2018).

Variable	Late century (2081-2100)	
	Business as usual (RCP-8.5)	Mitigation (RCP-4.5)
Projected average springtime temperature increase in the Sierra Nevada	7 degrees F	4 degrees F
Projected average springtime Sierra snowpack volume	36% of historic	70% of historic
Projected shift in runoff midpoint	50 days earlier	25 days earlier

Increasing air temperatures and shifts in the timing and amount of snowmelt runoff to streams is also projected to increase stream temperatures. Stream temperature is projected to increase differently across watersheds as a result of differences in watershed hydrology, climate projections, and elevation (Ficklin et al. 2013). Low elevation watersheds in the central and southern Sierra Nevada are projected to be more vulnerable to stream temperature increases, while watersheds in the northern Sierra and southern Cascades are projected to be slightly less vulnerable as the northern watersheds may have more subsurface flows that could lower stream temperature (Ficklin et al. 2013). Nevertheless, the average end-of-century increase in average annual stream temperature across Sierra Nevada watersheds is projected to be between 7.2 and 7.74°F, with the largest increases likely to occur in the spring and summer seasons, respectively (Ficklin et al. 2013). These rising stream temperatures are likely to negatively impact native cold-water fish and other aquatic organisms.

Finally, there will also be an increase in the frequency and severity of extreme events, including hotter, more severe, and more frequent droughts, and increased frequency and intensity of winter precipitation extremes and extreme floods (Garfin et al. 2013; Viers et al. 2013). al. 2013; Viers et al. 2013). There will also be an increased probability of high severity fire (Miller et al. 2009; Garfin et al. 2013).

Step 3: Assess climate vulnerabilities

This step involves identifying how the climate change projections and the current condition of the meadow might make each desired meadow restoration outcome vulnerable, and identifying the highest priority vulnerabilities to be addressed through restoration actions. A climate vulnerability is the susceptibility or amount of risk of a population or ecosystem to the negative impacts of climate change (Williams et al. 2008; Smit et al. 2000).

Vulnerability is made up of three components: sensitivity, exposure, and adaptive capacity. Sensitivity refers to the innate characteristics of a system or species, including such intrinsic factors as physiological tolerance limits, ecological traits, and genetic diversity (Williams et al. 2008; Glick et al. 2011). Sensitivity considers a system or species' tolerance to changes in climate variables such as temperature, precipitation, or other key processes. Exposure focuses on the character, magnitude, and rate of change in climate variability that the species or system is likely to experience (Glick et al. 2011). Finally, adaptive capacity refers to the ability of a species or system to accommodate or cope with climate change impacts (Glick et al. 2011). Adaptive capacity includes both evolutionary changes and plastic ecological responses as well as the capacity of humans to minimize impacts through management and/or restoration actions (Williams et al. 2000).

In the context of the Sierra meadow ecosystem, exposure would include the climate projections discussed in step two (e.g., changes to hydrology, increase in extreme events such as droughts and floods), while sensitivities would include how ecological processes (e.g., groundwater recharge, attenuation of peak flows) and meadow species (e.g., birds, amphibians) are likely to respond to such changes based on intrinsic characteristics (e.g., temperature tolerances of target species).

We recommend considering the following questions when assessing climate vulnerabilities for your restoration project:

- How do the climate change projections and the current condition of the meadow make each desired outcome vulnerable?
- Is the meadow's current condition capable of achieving the desired outcomes in the context of potential vulnerabilities?
- What are the priority vulnerabilities that should be addressed to ensure long-term project success?

The priority vulnerabilities identified in this step can be used in step four to identify climate-smart restoration actions to reduce these vulnerabilities and increase adaptive capacity. See Section II for a comprehensive list of example climate vulnerabilities in the context of achieving desired meadow restoration outcomes.

Step 4: Identify climate-smart restoration actions and adaptation approaches.

The last step of a vulnerability assessment process is integrating the results into adaptation approaches and to identify climate-smart restoration actions. Point Blue developed a set of principles to assist practitioners and restoration teams to develop climate-smart projects. These principles are based on watershed restoration principles and climate-smart tenants developed by National Wildlife Federation

(Stein et al. 2014) and Hansen et al. (2010). These principles can be applied to generate climate-smart restoration actions to address priority vulnerabilities. The principles are as follows:

1. **Show your work.** There is high uncertainty about how the climate will change and how society will respond. The information we use to guide action today may be very different from the information we use to guide action in the future. By showing our work, we help future generations continue to adapt as new information becomes available. Showing your work aids in arriving at the best possible actions, as you ask and answer key questions about the project.

2. **Look forward but don't ignore the past.** Because climate change will create conditions that are different from past and current ones, setting forward-looking goals is essential. Using the best available climate models at appropriate scales aids project design and likely increases the probability of long-term success. In cases where the available science is highly uncertain or divergent, restoration should be designed to succeed in multiple scenarios, with a recognition that ecosystems are dynamic, rather than static, entities. The past can also help in designing projects to succeed in the future. Information on a species' or ecosystem's response to historic climatic extremes can serve as a useful analog to how they might fare under predicted future scenarios.

3. **Consider the broader context.** Climate change does not act alone in stressing ecosystems. It is essential to consider and plan for the full range of threats to the system. Success of individual projects is influenced by the surrounding land use, ecological setting (e.g., hydrology), and future conditions at regional scales. A landscape-scale perspective reinforces the need to keep connectivity as a key characteristic of restoration to improve the potential for species to move in response to climate change and for preserving the ecological processes for evolutionary adaptations to climate change.

4. **Build in ecological insurance.** Restoration approaches that incorporate redundancies and are robust to a range of future scenarios may act to provide insurance against uncertain future conditions. Increasing redundancy in restoration means replicating and diversifying critical components (e.g., plant the full complement of willow species intermixed in high densities) and functions (e.g., building beaver dam analogs within projects that fill incised channels). High ecological diversity is a form of ecological insurance that could reduce the probability of ecosystem collapse if it buffers change in functional composition of the community, and there is relatively little risk in increasing it in restoration projects.

5. **Build evolutionary resilience.** It is increasingly recognized that micro-evolutionary change can occur at the relatively short timescales relevant to natural resource management decisions, and may therefore be a critical pathway by which species escape extinction under climate change. Consequently, restoration actions that build evolutionary resilience by managing microevolution are climate-smart. Evolutionary resilience can be accomplished by restoration projects that increase the size and connectedness of populations to allow for the maintenance of genetic variation and ongoing evolution in order to keep pace with climate change and may increase the probability that an ecosystem can recover after climatic extremes. It may also include assisted migration, which is the human-assisted movement of plants or animals to more climatically suitable habitats. In ecosystem restoration, assisted migration can take the form of

preferentially using genotypes best suited to the future predicted climate of the restoration site (Grady et al. 2011).

6. **Include the human community.** The long-term success and growth of climate-smart ecological restoration projects can be facilitated by a community of advocates with an understanding of the what, why, and how to prepare systems for climate change. Additionally, project sustainability may increase when people who understand and care about it can monitor and maintain it. Projects where citizen stewards are involved may be better supported and with increased influence.

7. **Monitor and experiment.** Given the great uncertainties around how climate change will impact ecosystems and how society will respond, it is important to conduct ecological monitoring to manage adaptively to a rapidly changing future. Restoration experiments can help answer key uncertainties, provide tools to access key information, and help evaluate effectiveness.

In the next section, we describe climate vulnerabilities specific to Sierra meadows and illustrate how the above principles can be used to design climate-smart restoration actions to address such vulnerabilities.

Section II: A vulnerability assessment for Sierra meadows

This section summarizes climate vulnerabilities and restoration actions identified for four riparian meadow restoration projects in the northern Sierra Nevada and southern Cascades region. These vulnerabilities and actions are not necessarily applicable to every project and are likely more applicable to riparian meadows with a stream channel and those located in the northern Sierra and at mid-elevations (5,000-8,000 feet). Because climate-smart restoration is a new field, it is important to note that some climate-smart actions recommended here are experimental and should be monitored closely in an adaptive management framework.

This section draws on the desired restoration outcomes, climate projections, and climate-smart restoration principles described in Section I to identify potential climate vulnerabilities associated with each outcome as well as actions to reduce such vulnerabilities and achieve desired conditions (see also Appendices B and C). This section is organized by our restoration outcomes, which are as follows:

- **Functional Meadow Hydrology.** The meadow exhibits hydrologic connectivity both laterally across the floodplain and vertically between surface and subsurface flows, contributing to groundwater recharge, late season stream flow, high water table, and attenuation and delay of peak flows.
- **Good Water Quality.** The meadow contributes to good water quality characterized by streams with low sediment outputs, low turbidity, and cool temperatures.
- **Healthy Meadow Soil.** The meadow features productive, healthy soil characterized by high levels of soil organic matter that have a high water holding capacity and net carbon sequestration.
- **Meadow Plant Species.** The meadow's hydrologic regime and forage utilization supports native meadow graminoid species and, where ecologically appropriate, riparian shrubs and trees of diverse age classes.
- **Meadow Wildlife.** The meadow supports diverse native terrestrial and aquatic wildlife, including birds, amphibians, and fish, that depend on meadows for some or all portions of their life cycle.
- **Resilience and Adaptive Capacity.** The meadow is resilient to and recovers from natural and human disturbances.

Our restoration outcomes are fundamentally interconnected. As such, there is a great deal of overlap between vulnerabilities and actions identified among the outcomes, and we may refer the reader to consult a different outcome for additional relevant recommendations. Additionally, we do not include a specific section for the last outcome, as our assumption is that implementing climate-smart restoration actions associated with the other outcomes will lead to increased resilience and adaptive capacity of the meadow to climate change and other disturbances. In the next section (Section III), we provide additional climate-smart best management practices to capture some recommendations that pertain to all of our desired restoration outcomes, such as managing livestock grazing, addressing other outside stressors, and crafting adaptive management and monitoring strategies.

Desired Outcome: Functional Meadow Hydrology

Our first desired restoration outcome is that the meadow exhibits hydrologic connectivity both laterally across the floodplain and vertically between surface and subsurface flows, contributing to groundwater recharge, late season stream flow, high water table, and attenuation and delay of peak flows. This outcome reflects a primary objective of riparian meadow restoration projects, which is to restore a floodplain appropriate to the riparian system. Designing actions to achieve this outcome should be informed by an understanding that there could be a range of flow and channel habitat types under natural conditions in riparian meadows depending on the geomorphic setting, such as self-formed, self-maintained alluvial channels (with or without additional side channels), or shallow channels with high width to depth ratios.

Achieving and maintaining hydrological connectivity and functioning hydrological processes may be vulnerable to projected changes in temperature, precipitation, and hydrology. These projections include more precipitation falling as rain than snow and loss of snowpack as a result of increasing temperatures, changes in the timing and amount of precipitation, and an increase in the frequency and severity of extreme events, including droughts and floods. Exposure to these changes will likely result in alterations to the flow regime in the meadow, characterized by a change in the mean annual flow volume, shift in centroid timing to earlier in the year, a longer period of low flow duration in the summer, and extreme high flow events (Viers et al. 2013).

Decreases in the mean annual flow volume may result in decreased runoff and decreased hydrological connectivity with the floodplain annually, reducing the amount of water available for the meadow to store as groundwater during the spring and summer. At the same time, there is likely to be a shift in centroid timing and peak flows to earlier in the year. As a result, groundwater levels might decrease earlier in the season, with low or no stream flow available in the late season, and the stream may become intermittent. Additionally, increasing temperatures and a longer growing season may lead to increased evapotranspiration and climatic water deficit, which may further modify the elevation of the water table; this may lead to declines in surface and shallow groundwater availability (Albano et al. in prep), as well as changes in plant species assemblages, which in turn may influence channel stability.

These vulnerabilities are likely to be exacerbated by an increase in the frequency and severity of extreme events, including droughts, floods, and high intensity rain events. An increase in rain-on-snow and heavy summer rain events may lead to periods of uncharacteristically high flows, which may incise the stream channel and decrease groundwater elevations in meadows with channels present (Viers et al. 2013); although this may be less likely to occur in systems characterized by an anastomosing stream network (Cluer and Thorne 2013). More frequent and intense droughts may reduce the availability of groundwater and surface water in the meadow. Extremes of drought and flood years, as well as high flow events from rain on snow and high intensity summer rains may lead to greater variability of flows than what has been observed historically.

Climate-smart actions associated with addressing meadow vulnerabilities related to hydrological connectivity and functioning center on the principle of building ecological insurance. The likelihood of greater variability in flows, extreme events, and uncertainty as to whether precipitation will increase or decrease will require restoration practitioners to incorporate redundancy into design elements and design projects that are likely to be successful under a range of possible future scenarios.

To address uncertainty about future conditions, the likelihood of greater variability in flows, and increases in extreme events, we recommend encouraging a multi-thread (anastomosing) channel system in the meadow that has the ability to adjust naturally to future changes in flow conditions. If the meadow is being restored using the pond and plug method, ensure that the upstream edge of each pond does not concentrate flow and that there is a minimal elevation differential from the plug above. Sedge mats, willows, and other riparian shrubs can be planted along re-occupied stream banks in order to help stabilize stream banks that may be at risk of degradation from high flow events.

To address potential decreases in channel-floodplain connectivity as a result of low flows, we recommend encouraging beaver occupancy of the restoration site where appropriate. This could include installing beaver dam analogs (BDAs) in order to help stream flows access the floodplain, and planting willows to ensure food and dam-building materials are available for beavers. Beavers can also help maintain the restoration over time. BDAs can be installed on top of filled material in projects that fill incised gullies to replicate floodplain activation, which may help provide insurance against uncertain future conditions. Maintaining areas with slow moving water into mid-summer through promoting backwaters, ponds (e.g. beaver), or other design elements can also help ensure water is available in the meadow in drought years or in years with low volumes of flow entering the meadow.

Desired Outcome: Good Water Quality

Our second desired restoration outcome is that the meadow contributes to good water quality characterized by streams with low sediment, low turbidity, and cool temperatures. The vulnerabilities to functional meadow hydrology discussed above as well as rising air temperatures, an increase in high severity wildfire, and changing plant species composition in the meadow may make meadow streams vulnerable to reduced water quality.

Many of the hydrological vulnerabilities discussed previously may also lead to water quality vulnerabilities. Very high flows following rain-on-snow events, high intensity summer rain events, and/or high severity wildfire may alter channel morphology that could increase the likelihood of channel degradation and incision, leading to more erosion and sediment inputs into the stream from stream banks. These high flow events may also lead to increased sediment inputs as a result of runoff from the upper watershed. Channel degradation, incision, and associated erosion may also occur as a result of decreased runoff and a shift in timing of peak flows to earlier in the year. These processes may result in loss of channel-floodplain connectivity and concomitant draining of the water table through the stream channel that would otherwise help to cool stream temperatures during base flow periods.

An increase in spring and summer air temperatures and changes in watershed hydrology may also lead to increased water temperatures in meadow stream channel(s). This could result in poor water quality for fish and amphibian species that require cool water temperatures, and may also lead to increased bacteria and nutrients, especially if cattle are allowed to graze in the meadow riparian area. Cattle may be more attracted to the stream channel for water and thermal refugia in response to warmer temperatures and drought. There may also be changes in plant composition in the meadow and upper watershed that may contribute to degraded water quality conditions, such as loss of riparian shrubs that stabilize stream banks from erosion and shade the stream channel. High severity wildfire in the upper watershed may lead to increased sediment input into the meadow from runoff. Increasing temperatures, an increase in climatic water deficit, and hydrological changes may lead to loss of wetland-associated plants and native hardwoods along the stream that stabilize stream channels and reduce erosion and turbidity.

Climate-smart actions associated with addressing meadow vulnerabilities related to water quality center on building ecological insurance and considering the broader watershed context. Addressing water quality vulnerabilities will require actions within the meadow restoration area as well as reducing stressors from the broader landscape. Many of the climate-smart actions for improving hydrological function and floodplain connectivity described previously may also help address water quality vulnerabilities by preventing degradation and incision of stream channels. Sedge mats, willows, and other riparian shrubs could be planted along stream banks to help stabilize and shade stream channels, prevent erosion, and capture sediment. These plantings should feature diverse species and be sourced from locations representing a range of environmental and climatic conditions in order to build in evolutionary resilience; this is discussed further in the section on meadow plant species.

Livestock Grazing: A Climate-Smart Approach

Livestock grazing is a stressor that poses vulnerabilities to all identified desired restoration outcomes. Livestock grazing can cause gullying, desiccation, shrub encroachment, and changes in plant species composition, structure, and diversity (Berlow et al. 2002; Dull 2004; Stillwater Sciences 2012). Livestock grazing and livestock congregation in or adjacent to the channel can remove plants from channel banks and contribute to bank erosion and bank failure (Trimble and Mendel 1995; Stillwater Sciences 2012). Grazing can also lead to soil compaction and soil disturbance, resulting in lower water infiltration and water holding capacity, reduced soil moisture, and increased surface runoff and erosion (Trimble and Mendel 1995; Stillwater Sciences 2012). Wildlife species, such as birds that nest in riparian shrubs or on the ground, can be impacted by trampling, browsing, and reduced ground cover (Stillwater Sciences 2012).

The following are some recommendations to reduce those vulnerabilities:

- Permanently or temporarily suspend cattle grazing within the meadow, especially during the sensitive period immediately after restoration.
- Reduce stocking rates, restrict cattle grazing to a limited portion of the growing season, restrict locations of the meadow where cattle have access, and/or change to a rest-rotation system.
- Fence off the riparian zone to address vulnerabilities to water quality and allow for germination and recruitment of willows and other riparian shrubs and trees, which can also help stabilize stream banks.
- Provide supplemental resources such as water, salt, and/or high-protein feed in a location that draws cattle away from the stream channel.

These practices can help improve forage production, reduce vulnerabilities to nesting birds, help maintain shrub cover, and minimize soil compaction and erosion (Schofield et al. in prep). Including periods of rest from grazing can also help vegetation recover and/or reestablish after direct interventions or disturbances, such as sites with a history of overgrazing (Schofield et al. in prep).

We also recommend developing and implementing an adaptive management and monitoring plan with triggers for management actions to help guide cattle grazing in direct response to site conditions. Some metrics that could be monitored and used in adaptive management include stubble height at the end of growing season, percent willow utilization and cover, plant species composition, and/or cover of bare soil (Schofield et al. in prep). Habitat and vegetation condition can also be monitored to address impacts to specific species conservation targets.

Several of the water quality vulnerabilities identified are related to landscape-scale factors and other stressors, including cattle grazing and high severity wildfire. The text box above provides some recommendations for reducing vulnerabilities associated with cattle grazing. High severity wildfire and forest management in the upper watershed can lead to downstream impacts to water quality within the meadow, requiring consideration of the broader watershed context. This could include participation in coordinated watershed management efforts to improve fire resiliency, maintain and enhance surface water flows, and reduce sediment inputs to the restoration site. One concrete action could be to install fuel breaks in proximity to the meadow designed to withstand extreme future fire weather.

Desired Outcome: Healthy Meadow Soil

There is increased interest by researchers and policymakers in the role that meadows can play in sequestering carbon. As a result, our third desired meadow restoration outcome is for the meadow to feature productive, healthy soil characterized by high levels of soil organic matter and high water holding capacity contributing to carbon sequestration.

Hydrological changes, increasing temperatures, an increase in climatic water deficit, and extreme drought may lead to vulnerabilities to meadow soil. One possible vulnerability is reduced future input of organic matter into the soil and loss of soil organic matter as a result of drier meadow conditions. This could be triggered by reduced water availability, a lowered water table from a lack of floodplain activation, increased climatic water deficit, and lack of late-season water. Another vulnerability may be an increase in decomposition of organic matter and soil volatilization as a result of an increase in climatic water deficit, increasing temperatures, and increased frequency and severity of extreme drought. These vulnerabilities may be exacerbated by cattle grazing, which can lead to loss of aboveground vegetation from herbivory as well as soil compaction. Compacted soils have reduced pore space for water infiltration and water retention, which in turn can reduce the capacity of soil to store carbon.

Reducing vulnerabilities to soil and ensuring that meadow soil has high levels of soil organic matter and high water holding capacity may be benefitted by the restoration of self-sustaining hydrological processes that keep meadows wet. As a result, the climate-smart restoration actions identified for reducing vulnerabilities to functional meadow hydrology are also applicable to reducing soil vulnerabilities. As mentioned above, cattle grazing also poses a vulnerability to soil health. We recommend permanently or temporarily suspending cattle grazing within the meadow to reduce impacts to soil and vegetation, especially during the sensitive period immediately after restoration and early in the growing season when the meadow is saturated with water and the soil soft and sensitive to compaction. If cattle grazing continues to be a long-term use within the meadow, consult the section on additional climate-smart best management practices for managing cattle grazing to reduce vulnerabilities to desired restoration outcomes.

Desired Outcome: Meadow Plant Species

Our fourth desired restoration outcome is for the meadow's hydrologic regime to support native meadow graminoid species, riparian shrubs, and trees of diverse age classes. Meadow plant species are vulnerable to hydrological changes that may lead to drier meadow conditions. Specifically, projected decreases in April 1 snowpack is likely to be a significant source of vulnerability to meadow vegetation vigor, especially for meadows at higher elevations (Albano et al., in prep).

Meadows may experience the loss of native wetland-associated plants and wet meadow obligates along with an increase in forbs and drier plant types. This conversion of the meadow to a more xeric community may be triggered by declines in April 1 snowpack and reduced water availability, especially during the late season, and lack of adequate runoff and flood disturbances to activate the floodplain and raise the groundwater table. Channel degradation and incision from extreme high flow years may also contribute to a drop in the groundwater table. This reduction in surface water runoff and groundwater recharge could be the result of inter-annual variability in precipitation, declines in April 1 snowpack, increased likelihood of extreme high flow and extreme low flow years, and increased frequency, intensity, and duration of drought. Climatic water deficit is also projected to increase, with implications for the persistence of wet meadow and wetland plant species. Temperature-induced increases in potential evapotranspiration will alter the water balance to support plant species and ecotypes currently found at lower elevations (Stephenson 2007), which may lead to a loss of wetland-associated plants. The drier conditions may encourage encroachment of fuels and native upland plants (e.g., lodgepole pine, shrubs) along the meadow edge. Conifer encroachment, as well as high severity fire, may also lead to loss of desired edge habitat. Encroaching conifers might also shade out willows, aspens, and other native riparian shrubs. Finally, changing meadow conditions may also make the meadow vulnerable to invasion by non-native plant species.

Climate-smart restoration actions to address vulnerabilities to meadow plant species can be identified by using several climate-smart principles, including building ecological insurance, building evolutionary resilience, considering the broader context, and monitoring and experimentation. The primary vulnerability to meadow species is drier meadow conditions that may make individual species vulnerable and lead to changes in species composition. As a result, many of the climate-smart actions aimed at restoring functional meadow hydrology are applicable here.

In addition to restoring functional meadow hydrology, we also recommend active revegetation of the meadow as part of the restoration process. Designing restoration plantings and identifying the species planting palette should be guided by the principles of building evolutionary resilience and redundancy. Maintaining and enhancing the genetic diversity of meadow plant species is key to allow species to adapt in response to changing conditions and to ensure the persistence of important ecological processes (Harris et al. 2006; Swanston et al. 2016; Aavik and Helm 2018). Because future climate conditions remain uncertain, we recommend including a broad mix of regionally native but locally novel genotypes or species adapted to current and various projected future conditions and disturbance regimes (Perry et al. 2016). Genetic diversity can also be increased by sourcing seeds, willow cuttings, and other plant genetic material from across a large geographic range (Harris et al. 2006; Swanston et al. 2016; Aavik and Helm 2018).

Diversifying the species composition of plantings should also promote functional redundancy to ensure that the functional roles played by various species are likely to persist even if changing ecological conditions may lead to stress or direct mortality of individuals. Maintaining and enhancing biodiversity, structural diversity, and functional diversity can increase ecosystem redundancies and confer resilience (Swanston et al. 2016; Perry et al. 2016; Aslan et al. 2018). For example, this could involve planting the full diversity of riparian deciduous shrubs that occur in the vicinity of the meadow restoration site. Another recommendation is participating in efforts to increase landscape-scale connectivity that may help facilitate natural species dispersal and colonization of the meadow after restoration (Aavik and Helm 2018; Addington et al. 2018). We also recommend considering a phased revegetation approach and selecting a vegetation palette that can help prevent invasion of the restoration site by non-native species and upland plants. This could involve planting native early colonizers that can compete with invasives and encouraging regeneration of dense sedge mats to inhibit conifer encroachment.

Traditional ecological restoration approaches recommend sourcing seeds and plants from within close proximity to the restoration site, with the assumption being that those individuals are best adapted to those local conditions. However, climate-smart restoration requires forward-looking goals and strategies that center on ensuring the persistence of species under a range of different projected future conditions. This requires focusing less on restoring historic community composition and instead focusing on restoring desired functions and building in resilience through diversity and redundancy (Perry et al. 2015). The recommended actions listed here involve some degree of experimentation and risk-taking; as such, we recommend that practitioners "show their work" and monitor the results of revegetation processes to evaluate whether they were successful in reaching desired meadow outcomes and addressing identified vulnerabilities.

Desired Outcome: Meadow Wildlife

Healthy meadows provide habitat for diverse terrestrial and aquatic species, some of which are rare and declining and in urgent need of conservation action. As a result, one of our desired restoration outcomes is that the meadow supports diverse native meadow-dependent terrestrial and aquatic species, including birds, amphibians, and fish. Achieving this outcome is directly linked to achieving the other desired restoration outcomes discussed previously. In this section, we focus on identifying vulnerabilities to species and ecological communities, with the caveat that many of the vulnerabilities and climate-smart restoration actions listed in the previous sections are also applicable.

Changing hydrological conditions, most notably alterations to the timing, duration, and volume of surface and ground water available in the meadow as well as reductions in the frequency of flood disturbances, may lead to vulnerabilities to species and species interactions. One vulnerability is reduced aquatic habitat for fish and amphibians, which may be further aggravated by an increase in the frequency and severity of drought. Additionally, changes to water availability may result in phenological mismatches among hydrology, plants, and animals. A shift in the hydrograph toward earlier in the year may cause flowers to be unavailable when birds are migrating, fruit to be unavailable for birds in late summer, and a mismatch between when flood waters recede and riparian shrub seeds set. Similarly, changing temperature and precipitation patterns may change the timing of invertebrate emergence, with implications for species that rely on invertebrates as a food source as well as for plant pollination.

Species may also be vulnerable to novel temperature and precipitation conditions, including increasing spring and summer temperatures as well as extreme summer precipitation and heat events. This may lead to increased competition among species for thermal refugia, and may result in mortality to individuals through direct exposure to extreme conditions. There may also be an increase in fungi affecting amphibians and plants as a result of increasing temperatures and changing precipitation patterns. Extreme drought, lowered water table, and reduced water availability may also lead to the loss of willows, making meadow habitat unsuitable for beaver, yellow warbler, willow flycatcher, and many other target species. Increasing temperatures and reduced water availability may lead to water temperatures outside the thermal tolerance of some fish and amphibians as well as a lack of instream habitat, especially during the late summer months when there is reduced runoff.

Meadow habitat is also vulnerable to extreme events, such as droughts and wildfires. These events may lead to conditions that may make the meadow susceptible to conifer encroachment and invasion by non-native species that may outcompete native wetland and wet meadow vegetation. In particular, conifer encroachment may reduce the availability of meadow edge habitat used by great gray owl and other species for nesting and predation. Very high flows, sedimentation, and/or excessive woody debris following rain-on-snow events, heavy summer rain events, and/or high severity wildfire may lead to channel degradation and incision as well as increased sediment loads, creating poor water quality conditions for aquatic organisms.

Addressing the identified vulnerabilities to meadow habitat are directly related to implementing previously identified climate-smart actions that will help reach our other desired restoration outcomes. For example, many meadow-dependent species are vulnerable to changes in the timing, amount, and duration of water in the meadow, requiring actions that will contribute to functional meadow hydrology. Maintaining areas with ponded slow moving water through design elements can help maintain and enhance water availability. To address vulnerabilities to aquatic organisms dependent on cold, clean water, we recommend protecting and restoring riparian vegetative cover along stream channels to provide shade, decrease the potential for rising stream temperatures and associated negative impacts, reduce exposure, stabilize stream banks, and capture sediment (Addington et al. 2018).

To address vulnerabilities associated with decreases in food availability and potential phenological mismatches, we recommend building in ecological insurance by planting a diverse mix of riparian shrubs and trees along the stream channel, meadow edges, and other moisture gradients to increase the number of months that fruits and flowers are available. To address vulnerabilities associated with changing climatic conditions that may be outside the tolerance of some species, we recommend designing climate-smart planting palettes with diverse species and genotypes as described under the meadow plants outcome. Thermal refugia and microhabitat for species can be designed by strategically planting willows to promote large clumps of dense foliage with diverse plant understories near water.

Section III: Additional climate-smart best management practices

The climate-smart actions identified above represent some specific, concrete management actions that can be undertaken to reduce meadow vulnerabilities to climate change. These actions have largely centered on the climate-smart principles of building in ecological insurance and evolutionary resilience as well as considering both past and future conditions to develop actions robust to uncertainty. There are also additional climate-smart best management practices that have not been thoroughly discussed in the context of each desired restoration outcome that are nevertheless important to integrate into restoration projects. These practices include: (1) considering the broader context to address outside stressors, (2) experimentation and risk evaluation, (3) developing adaptive management and monitoring strategies, and (4) including the human community. These practices apply to vulnerabilities across our identified restoration outcomes.

Consider the broader context

The vulnerabilities identified in this handbook have centered on climate change as a source of disturbances (e.g., extreme floods) and stress (e.g., less precipitation, increased temperatures) to meadow restoration projects. However, there are likely to be additional stressors that may have contributed to past meadow degradation and subsequent need for restoration, as well as those that might threaten to degrade the meadow after desired restoration outcomes have been achieved. Considering the broader context of your meadow restoration project is essential to ensure that all past and potential stressors are identified and addressed as part of the restoration design process (Hobbs and Norton 1996; Swanston et al. 2016). The success of individual projects can be influenced by surrounding land uses (e.g., water diversions, agricultural uses, development, forestry activities), landscape conditions (e.g., condition of road networks, presence of invasive species in adjacent sites), and potential uses of the meadow post-restoration (e.g., livestock grazing, recreation). These potential stressors can be exacerbated by climate change, and mitigation of these stressors can help increase meadow resiliency. Integration of the restored meadow into the larger landscape can be stated explicitly as a goal of the restoration project, as well (Aavik and Helm 2018).

We recommend participating in watershed-scale efforts to coordinate, design, and implement additional restoration and management projects in the watershed and adjacent uplands to increase landscape-scale connectivity and improve ecosystem functioning across a larger scale than an individual meadow alone. Improving connectivity can improve the ability of species to disperse to new habitat patches in response to changing environmental conditions, facilitating adaptation (Aavik and Helm 2018; Addington et al. 2018). Ameliorating other stressors, like forest densification or erosion from roads, may be critical to increasing meadow resiliency and ability to cope with climate vulnerabilities.

Experimentation and risk

Many of the climate-smart restoration actions identified to address vulnerabilities involve a degree of experimentation, such as sourcing species for planting from distant locales or planting a diverse mix of species to increase redundancy and evolutionary resilience. Such monitoring and experimentation is an essential component of climate-smart restoration. Restoration experiments can help answer questions about uncertainties as to how the climate will change and how species and ecosystems will respond, as well as which approaches are most effective to address different vulnerabilities. When designing restoration projects that may include experimental climate-smart actions to address vulnerabilities, it is important to "show your work." Showing your work means recording how and why you made certain decisions and which actions were actually taken, as well as implementing monitoring to evaluate the effectiveness of different actions and strategies. The results of monitoring in the context of the original decision-making process can be used to adjust strategies and approaches as needed in response to new information and lessons learned. Such documentation can also help provide information to other meadow restoration practitioners, contributing to a knowledge base of climate-smart restoration actions that can be used to inform future restoration projects.

Experimentation with restoration design may come with additional risk, which must be weighed against potential benefits. In the context of climate-smart restoration, it's helpful to think about (1) the likelihood that the vulnerability will manifest and the certainty of the associated climate projection, (2) the impact of the vulnerability if it manifests, (3) the likelihood of an action's success at addressing a vulnerability, and (4) the potential for an action's maladaption (Figure 2). The likelihood of a vulnerability manifesting depends on uncertainties around climate projections and relevant gaps in our knowledge of the ecology of the system. If the vulnerability does not manifest, resources spent developing and implementing a potential action may have been wasted. If the vulnerability does manifest, then there is risk in the integrity of the project if a designed action fails to address the vulnerability or if no action was taken; that risk increases as the impact of the vulnerability on the project increases. If the potential vulnerability has large consequences for the core outcomes of the project, you may be willing to experiment with actions that you are less confident will succeed if no other options exist.

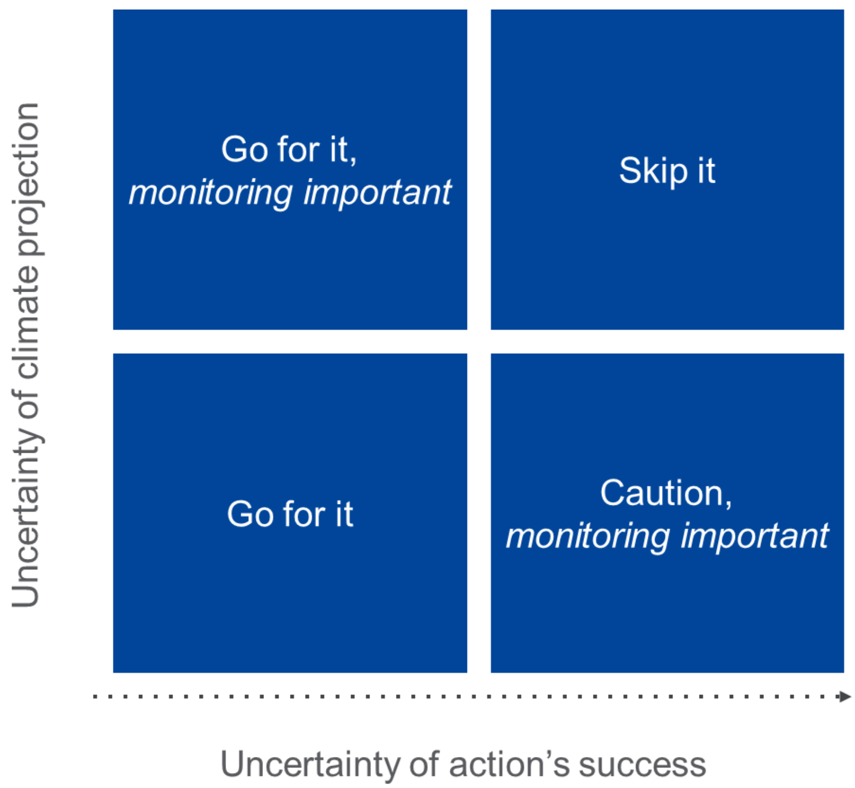

Figure 2: A framework for evaluating risk in the context of designing and implementing climate-smart restoration actions.

Maladaption in this context is an action that becomes more harmful than helpful, or an action that has unintended negative consequences. The risk for maladaptation may be independent of an action's success at addressing a vulnerability, but can be weighed against a vulnerability's potential impact. If the potential for maladaption for a given action is high or highly uncertain, you may be much less likely to experiment with it, regardless of your confidence in the action's success. You may be more willing, however, to risk maladaptation of an action if the vulnerability it addresses is critical to the outcomes of the project.

Tolerance for risk of spending monetary resources, project failure, and maladaptation will differ among stakeholders and agencies or even within a restoration team, which will result in variable implementation strategies and actions among projects to address similar vulnerabilities. Nevertheless, all projects should implement no-regrets actions — those that are cheap, effective, and have little to no chance for maladaptation — regardless of the likelihood that the vulnerability the action is designed to address will manifest.

Adaptive management and monitoring

We also recommend developing and implementing an adaptive management and monitoring plan for your meadow restoration project. Adaptive management is particularly appropriate for projects designed explicitly in the context of climate change, as this approach deliberately seeks to address uncertainties in management through experimentation (Addington et al. 2018). An adaptive management and monitoring plan can be used to evaluate project performance, assess the success of different climate-smart restoration actions in addressing identified vulnerabilities, identify needed management actions, and evaluate and address risk-taking. When designing an adaptive management and monitoring plan, we recommend including metrics for each of your desired meadow restoration outcomes, objectives, and/or conservation targets (e.g., wetland plants, soil, hydrology) along with triggers for management actions. For example, if livestock grazing will occur post-restoration, your plan might include triggers (e.g., forage height, precipitation) that would indicate when livestock grazing should be reduced, altered, or paused until a certain condition is met. Additionally, the time scale for implementation of the monitoring strategy should be designed to reflect the temporal scale at which desired outcomes might be realized. For instance, if a desired outcome is to increase soil organic carbon in the meadow post-restoration, monitoring should occur on a longer timescale (e.g., 5-10 years) to account for the time lag before which such changes might be realized (Herrick et al. 2006; Addington et al. 2018). Long-term monitoring should be maintained whenever possible to assess restoration outcomes, adjust restoration goals and strategies, and adapt the long-term management strategy for the site post-restoration (Choi et al. 2004; Herrick et al. 2006). Climate-smart meadow restoration calls for a long-term commitment to steward the site to ensure significant investment in restoration is realized over the long-term as conditions change.

Include the human community

Finally, we recommend including your local community in meadow restoration when possible. Doing so increases local support for restoration, understanding of ways to adapt to climate change, and gives people from students to adults examples of how local actions result in tangible, on-the ground impacts. Here are a few examples:

- Engage the local community early in the restoration planning process, such as by hosting field tours of the site.
- Include schools and volunteers in the actual restoration. Lay people can be trained to engage meaningfully in professional restoration projects. For more information, visit https://www.pointblue.org/our-work/education/ for an example of how this can work.
- Consider developing signage for publicly accessible sites.
- Invite community newspapers and newsletters to highlight the restoration project to your community.
- Organize local volunteers as project stewards to help monitor and maintain young restoration projects.
- Work with local nature education partners to host walks and field trips for school and adult community groups.
- Get creative and choose ideas that meet the needs of your community.

Conclusion

We are already experiencing the effects of climate change in the Sierra Nevada. Projections suggest that the region is likely to continue to experience profound changes through the end of the 21st century. Rising temperatures, reduced snowpack, changing hydrological conditions, and increased frequency and intensity of extreme events threaten Sierra meadows and meadow-associated species. Restoring Sierra meadows in the context of historical conditions and the range of historic variability is unlikely to be adequate to ensure that desired meadow restoration outcomes, such as hydrological processes and habitat for diverse species, are able to persist under future climate change. Instead, we recommend that practitioners engage in climate-smart restoration, which we define as the process of enhancing ecological function of degraded, damaged, or destroyed areas in a manner that makes them resilient to the consequences of climate change.

This handbook illustrates how practitioners can integrate climate change considerations into planning and design for Sierra meadow restoration projects. The concepts, approaches, and best management practices included in this handbook can be used to increase the resilience of meadows in the context of climate change. For practitioners interested in learning more about climate adaptation planning and exploring complementary approaches, we recommend integrating scenario planning (Moore et al. 2013) or strategic foresight (Cook et al. 2014a,b) into the restoration design process. Such approaches complement vulnerability assessments by further evaluating multiple possible futures and selecting possible pathways that may help promote the most desirable future scenario (Cook et al. 2014a,b).

We encourage restoration practitioners to engage in experimentation with the design and implementation of climate-smart restoration actions both by drawing on those identified in this handbook as well as designing new and innovative climate-smart restoration and management actions. Future climatic and environmental conditions are uncertain, requiring creativity, thoughtfulness, and a willingness to try new approaches in order to increase the likelihood that the desired outcomes of restoration projects will be resilient to future change. Showing your work, engaging in monitoring, and sharing results with other practitioners are essential components of climate-smart restoration that directly complement the experimental nature of climate-smart restoration. Keeping a record of how you made decisions and the underlying assumption will be invaluable when assessing the effectiveness of restoration actions to achieving desired outcomes through future monitoring and project evaluation. Finally, we encourage communicating the results of climate-smart restoration projects with other practitioners, researchers, and others in order to facilitate learning and increase the likelihood that other climate-smart restoration projects are successful in meeting desired outcomes.

Acknowledgments

This work was funded by the Volgenau Foundation and Bella Vista Foundation. Special thanks to T. Gardali, C. Oehrli, M. Pitkin, and S. Yarnell for their review of the handbook.

References

Aavik, T. and A. Helm. 2018. Restoration of plant species and genetic diversity depends on landscape-scale dispersal. Restoration Ecology 26(S2): S92-S102.

Addington, Robert N.; Aplet, Gregory H.; Battaglia, Mike A.; Briggs, Jennifer S.; Brown, Peter M.; Cheng, Antony S.; Dickinson, Yvette; Feinstein, Jonas A.; Pelz, Kristen A.; Regan, Claudia M.; Thinnes, Jim; Truex, Rick; Fornwalt, Paula J.; Gannon, Benjamin; Julian, Chad W.; Underhill, Jeffrey L.; Wolk, Brett. 2018. Principles and practices for the restoration of ponderosa pine and dry mixed-conifer forests of the Colorado Front Range. RMRS-GTR-373. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 121 p.

Albano, C. M., M. L. McClure, S. E. Gross, W. Kitlasten, C. E. Soulard, C. Morton, and J. Huntington. In prep. Spatial patterns of meadow sensitivities to interannual climate variability in the Sierra Nevada.

Aslan, C. E., B. Peterson, A. B. Shiels, W. Haines, and C. T. Liang. 2018. Operationalizing resilience for conservation objectives: the 4S's. Restoration Ecology doi:10.1111/rec.12867

Berlow, E. L., C. M. D'Antonio, and S. A. Reynolds. 2002. Shrub expansion in montane meadows: The interaction of local-scale disturbance and site aridity. Ecological Applications 12(4), 1103-1118.

California Natural Resources Agency, California Department of Food and Agriculture and California Environmental Protection Agency 2014. California Water Action Plan. Accessed 8/12/2016 http://resources.ca.gov/docs/Final_Water_Action_Plan_Press_Release_1-27-14.pdf

Choi, Y. D. 2004. Theories for ecological restoration in changing environment: Toward 'futuristic' restoration. Ecological Research 19: 75-81.

Cluer, B. and C. Thorne. 2013. A stream evolution model integrating habitat and ecosystem benefits. River Research and Applications. DOI: 10.1002/rra.2631

Cook, C. N., B. C. Wintle, S. C. Aldrich, and B. A. Wintle. 2014. Using strategic foresight to assess conservation opportunity. Conservation Biology 28(6), 1474-1483.

Cook, C. N., S. Inayatullah, M. A. Burgman, W. J. Sutherland, and B. A. Wintle. 2014. Strategic foresight: how planning for the unpredictable can improve environmental decision-making. Trends in Ecology and Evolution, 29(9), 531-541.

Drew, W. M., N. Hemphill, L. Keszey, A. Merrill, L. Hunt, et al. 2016. Sierra Meadows Strategy. Sierra Meadows Partnership Paper 1: PP 40.

Dull, R. A. 2004. Palynological evidence for 19th century grazing-induced vegetation change in the southern Sierra Nevada, California, U.S.A. Journal of Biogeography, 26, 899-912.

Ficklin, D. L, I. T. Stewart, and E. P. Maurer. 2013. Effects of climate change on stream temperature, dissolved oxygen, and sediment concentration in the Sierra Nevada in California. Water Resources Research 49, 2765-2782.

Flint, L., A. Flint, J. Thorne, and R. Boynton. 2014. California Basin Characterization Model (BCM) downscaled climate and hydrology. California Climate Commons. Accessible online at http://climate.calcommons.org/dataset/2014-CA-BCM

Garfin, G. A., A. Jardine, R. Merideth, M. Black, and S. LeRoy, eds. 2013. Assessment of climate change in the Southwest United States: A report prepared for the National Climate Assessment. A report by the Southwest Climate Alliance. Washington, D.C.: Island Press.

Glick, P., B. A. Stein, and N. A. Edelson, eds. 2011. Scanning the conservation horizon: A guide to climate change vulnerability assessment. National Wildlife Federation, Washington, D. C.

Grady, K. C., S. M. Ferrier, T. E. Kolb, S. C. Hart, G. J. Allan, and T. G. Whitham. 2011. Genetic variation in productivity of foundation riparian species at the edge of their distribution: Implications for restoration and assisted migration in a warming climate. Global Change Biology 17(12): 3724-3735.

Hansen, L., J. Hoffman, C. Drews, E. Mielbrecht. 2010. Designing climate-smart conservation: guidance and case studies. Conservation Biology 24:63–69.

Harris, J. A., R. J. Hobbs, E. Higgs, and J. Aronson. 2006. Ecological restoration and global climate change. Restoration Ecology 14(2), 170-176.

Herrick, J. E., G. E. Schuman, and A. Rango. 2006. Monitoring ecological processes for restoration projects. Journal for Nature Conservation 14, 161-171.

Hobbes, R. J. and D. A. Norton. 1996. Towards a conceptual framework for restoration ecology. Restoration Ecology 4(2): 93-110.

Livneh, B., T. J. Bohn, D. W. Pierce, F. Munoz-Arriola, B. Nijssen, R. Vose, D. R. Cayan, and L. Brekke. 2015. A spatially comprehensive, hydrometeorological data set for Mexico, the U.S., and Southern Canada 1950-2013. Scientific Data 2, Article Number 150042.

Miller, J. D., H. D. Safford, M. Crimmins, and A. E. Thode. 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade mountains, California and Nevada, USA. Ecosystems 12: 16-32.

Moore, S. S., N. E. Seavy, and M. Gerhart. 2013. Scenario planning for climate change adaptation: A guide for resource managers. Point Blue Conservation Science and California Coastal Conservancy.

Mote, P. W. and D. Sharp. 2016 update to data originally published in: 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.

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.

Mote, P.W., S. Li, D. P. Lettenmaier, M. Xiao, and R. Engel. 2018. Dramatic declines in snowpack in the western US. Climate and Atmospheric Science 1, 2.

National Fish and Wildlife Foundation. 2010. Sierra Nevada Meadow Restoration Business Plan. Available online at https://www.nfwf.org/sierranevada/Documents/Sierra_Meadow_Restoration_business_plan.pdf.

Northern Institute of Applied Climate Science. Accessed 28 November 2018. Adaptation Workbook. Available online at adaptationworkbook.org.

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., L. V. Reynolds, T. J. Beechie, M. J. Collins, and P. B. Shafroth. 2015. Incorporating climate change projections into riparian restoration planning and design. Ecohydrology 8(5), 863-879.

Pierce, D. W., D. R. Cayan, and B. L. Thrasher. 2014. Statistical downscaling using localized constructed analogs (LOCA). Journal of Hydrometeorology, 15, 2558-2585.

Reich, K. D., D. B. Walton, M. Schwartz, F. Sun, X. Huang, and A. Hall. 2018. Climate change in the Sierra Nevada: California's water future. UCLA Center for Climate Science.

Rhoades, A. M., A. D. Jones, and P. A. Ullrich. 2018. The changing character of the California Sierra Nevada as a natural reservoir. Geophysical Research Letters, 45. doi.org/10.1029/2018GL080308.

Schofield, L. N., H. L. Loffland, R. B. Siegel, C. Stermer, and T. Mark. In prep. A conservation strategy for Willow Flycatcher (*Empidonax trailli*) in California. Interim version 1.0. The Institute for Bird Populations. Point Reyes Station, California.

Smit, B., I. Burton, R. J. T. Klein, and J. Wandel. 2000. An anatomy of adaptation to climate change and variability. Climate Change 45: 223-251.

Stein, B.A., P. Glick, N. Edelson, and A. Staudt (eds.). 2014. Climate-Smart Conservation: Putting Adaptation Principles into Practice. National Wildlife Federation, Washington, D.C.

Stephenson, N. 1998. Actual evapotranspiration and deficit: Biologically meaningful correlates of vegetation distribution across spatial scales. Journal of Biogeography 25(5): 855–70.

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.

Swanston, Christopher W.; Janowiak, Maria K.; Brandt, Leslie A.; Butler, Patricia R.; Handler, Stephen D.; Shannon, P. Danielle; Derby Lewis, Abigail; Hall, Kimberly; Fahey, Robert T.; Scott, Lydia; Kerber, Angela; Miesbauer, Jason W.; Darling, Lindsay. 2016. Forest Adaptation Resources: climate change tools and approaches for land managers, 2nd ed. Gen. Tech. Rep. NRS-GTR-87-2.

Trimble, S. W. and A. C. Mendel. 1995. The cow as a geomorphic agent – A critical review. Geomorphology 13, 233-253.

USDA Forest Service. 2015. Region 5 Ecological Restoration Leadership Intent. Available online at http://www.fs.usda.gov/Internet/FSE_DOCUMENTS stelprdb5351674.pdf.

Veloz, S. D., N. Nur, L. Salas, D. Jongsomjit, J. K. Wood, D. Stralberg, and G. Ballard. 2013. Modeling climate change impacts on tidal marsh birds: Restoration and conservation planning in the face of uncertainty. Ecosphere. **4**:49. http://dx.doi.org/10.1890/ES12-00341.1

Watershed Improvement Program. 2016. Sierra Nevada Watershed Improvement Program Regional Strategy. http://restorethesierra.org/wp-content uploads/2016/02/WIP_Reg_Strat_FINAL-PROOFED-7_25_16_ReducedSize.pdf

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

Williams, S. E., L. P. Shool, J. L. Isaac, A. A. Hoffmann, and G. Langham. 2008. Towards an integrated framework for assessing the vulnerability of species to climate change. PLoS Biology 6(12): 2621-2626.

Appendix A: Project Planning Worksheet

This worksheet offers a structured process that you can use to identify climate vulnerabilities to your desired meadow restoration outcomes and objectives and design actions that can increase the resilience of your project to identified vulnerabilities. The steps in this worksheet are based on Glick et al. 2011 and the Northern Institute of Applied Climate Science's Adaptation Workbook.

Step 1: Define objectives and desired outcomes.

The first step is to define your desired outcomes and project objectives. These outcomes represent desired conditions for the meadow post-restoration and can also serve as the basis for establishing meadow restoration project objectives. Objectives are specific, measurable results of your project and can be used to assess whether desired outcomes have been reached. Section I of this handbook provides a comprehensive list of desired meadow restoration outcomes that can serve as a starting point or basis for developing your own. Use the table below to define your project objectives and desired outcomes.

Desired Outcomes	**Objectives**
Example: The meadow supports diverse native meadow-dependent terrestrial and aquatic wildlife, including birds, amphibians, and fish.	*Example:* *(1) Increase willow cover to 30% of the meadow area to support willow flycatchers.*

Step 2: Gather relevant data.

The next step is to gather relevant data on climate projections for your project area. These projections will be the basis for identifying vulnerabilities to your desired restoration outcomes in the next step. Some sources include Cal-Adapt, California Basin Characterization Model, and California Climate Commons. Section I of this handbook also provides a summary of climate projections for the Sierra Nevada that can be used as a starting point. Use the text box below to record your findings.

Climate models and emissions scenarios used:

Example: HadGEM2-ES, CNRM-CM5, CanESM2, and MIROC5, under RCP 8.5

Summary of climatic projections for the project area:

Example: The number of extreme heat days per year projected to increase on average from a historic baseline of 6 days/year in 1981-2010 to 33 days/year by mid-century (2041-2060).

Step 3: Assess climate impacts and vulnerabilities in the context of desired outcomes.

This step involves identifying how the climate change projections and the current condition of the meadow might make each desired outcome vulnerable, and identifying the highest priority vulnerabilities to be addressed through restoration actions. A vulnerability is the susceptibility or amount of risk of a population or ecosystem to negative impacts (Williams et al. 2008; Smit et al. 2000). Assessing climate vulnerability seeks to determine how susceptible a species or system is to the negative impacts of climate change. The following are some questions to consider:

- How do the climate change projections and the current condition of the meadow make each desired outcome vulnerable?
- Is the meadow's current condition capable of achieving the desired outcomes in the context of potential vulnerabilities?
- What are the priority vulnerabilities that should be addressed to ensure long-term project success?

You can draw on the vulnerabilities summarized in Section II and Appendix B of this handbook or identify your own based on your desired outcomes and data collected in step 2. Use the table below to list your priority vulnerabilities.

Desired Outcomes	**Priority Vulnerabilities**
Example: The meadow supports diverse native meadow-dependent terrestrial and aquatic wildlife, including birds, amphibians, and fish.	*Example: Extreme heat events cause mortality through direct exposure.*

Step 4: Identify climate-smart restoration actions and adaptation approaches.

This step involves identifying climate-smart restoration actions that can reduce or address the vulnerabilities identified in step 3 using Point Blue's climate-smart restoration principles. These principles are shown in the text box and detailed in Section I of the handbook. Consider the following questions:

- How can Point Blue's climate-smart principles be applied to generate climate-smart actions to address one or more priority vulnerabilities?
- What restoration actions can be taken to address one or more priority vulnerabilities?
- What are the priority actions that should be taken to ensure long-term project success?

Pont Blue's climate-smart restoration principles:

1. Show your work.
2. Look forward but don't ignore the past.
3. Consider the broader context.
4. Build in ecological insurance.
5. Build evolutionary resilience.
6. Include the human community.
7. Monitor and experiment.

You can draw on the climate-smart restoration actions summarized in Section II and Appendix C of this handbook or identify your own based on your desired outcomes and vulnerabilities identified in step 3. List your identified actions for each priority vulnerability in the table below.

Priority Vulnerabilities	**Climate-Smart Restoration Actions**
Example: Extreme heat events cause mortality through direct exposure.	*Examples:* *(1) Plant willows and other riparian shrubs along stream banks to shade the stream.* *(2) Source species for plantings from areas lower in the watershed that are warmer and drier.*

Step 5: Monitor effectiveness of implemented actions.

The final step is developing an adaptive management and monitoring plan for your project to evaluate the effectiveness of your restoration actions in reducing identified vulnerabilities and meeting desired outcomes and objectives. For each objective and/or desired restoration outcome, identify metrics that can be used to evaluate whether the project is on track to meet those objectives and outcomes along with a monitoring approach to guide data collection. We also recommend establishing targets for these metrics with associated triggers for management actions. Here are some questions to consider when developing this plan:

- What are the metrics and monitoring strategy for each desired restoration outcome that you will use to evaluate the effectiveness of your project in reducing vulnerabilities and achieving desired outcomes?
- What are the threshold values for each metric that indicate either success or need for further management interventions?

Long-term monitoring should be maintained whenever possible to assess restoration outcomes, adjust restoration goals and strategies, and adapt the long-term management strategy for the site post-restoration. Use the table on the next page to plan your monitoring strategy.

Desired Outcomes	**Objectives**	**Monitoring Indicator/Metric**	**Frequency of Collection**	**Trigger for Action**
The meadow supports diverse native meadow-dependent terrestrial and aquatic wildlife, including birds, amphibians, and fish.	*Increase willow cover to 30% of the meadow area to support willow flycatchers.*	*Willow cover*	*Every 4-5 years*	*Before 30% willow cover attained: Percent cover declines or increases by less than 2% of meadow area in consecutive assessments.* *After 30% cover achieved: Percent cover dips below 27%.*

Appendix B: Vulnerabilities to Meadow Restoration Outcomes

The following tables list climate vulnerabilities associated with each desired meadow restoration outcome, along with the plausible proximate cause of that vulnerability.

Desired Outcome: Functional Meadow Hydrology	
Climate Vulnerability	**Plausible Proximate Cause**
Earlier peak discharge	Higher proportion of winter precipitation falling as rain.
	Shift in timing of peak flows to earlier in the year.
	Decreased snowpack.
Water not infiltrating over entire floodplain	Decreased runoff resulting in decreased hydrological connectivity.
Less water being stored as groundwater in spring and summer	Increased climatic water deficit in meadow.
	More frequent and intense drought.
	Conifer encroachment.
	Reduction in precipitation results in less water flowing through meadow.
	Higher proportion of winter precipitation falling as rain.
Change in vegetation or soil state results in reduced infiltration rate	Increasing temperatures.
	Reduced inflow into meadow.
	Loss of deep-rooted vegetation.
	Increased climatic water deficit in meadow.
Increased likelihood of channel degradation and incision dropping water table	Very high flows, sedimentation, and/or woody debris following rain-on-snow events, heavy summer rain events, and/or high severity wildfire.
	Loss of wetland-associated plants and riparian shrubs/trees that stabilize stream channels.
	Changes in timing and amount of water and greater variability in flows, leading to shifts in timing of peak flows to earlier in the year and lack of adequate water to fill channel or activate floodplain.
Groundwater table drains earlier in the season with low or no stream flow available late in the season	Decreased runoff resulting in decreased hydrological connectivity.
	Shift in timing of peak flows to earlier in the year.
	Conifer encroachment.
Stream may become more intermittent	Decreased runoff resulting in decreased hydrological connectivity.
	Shift in timing of peak flows to earlier in the year.
	Greater variability in flows as a result of extremes of drought and flood years as well as intra-seasonal variability in flows.

Desired Outcome: Good Water Quality	
Climate Vulnerability	**Plausible Proximate Cause**
Increased likelihood of channel degradation and incision leading to erosion	Very high flows, sedimentation, and/or woody debris following rain-on-snow events, heavy summer rain events, and/or high severity wildfire.
	Loss of wetland-associated plants and riparian shrubs/trees that stabilize stream channels.
Increased water temperature contributes to poor water quality	Increase in spring and summer temperatures.
	Loss of riparian shrubs/trees that shade streams.
	Decreased runoff and water volume in stream channel(s).
Increased bacteria and nutrient loads	Warmer water temperatures.
	Cattle grazing in riparian zone.
Increase in fungi that negatively affect amphibians and plants	Increase in summer temperatures
	Increase in proportion of precipitation falling as rain.
	Potential increase in precipitation.
Increased sediment input	Extreme events, including flash floods, high volume storms, and rain on snow events contributing to high flows.
	Forest conversion to shrub-dominated community in upper watershed from fires.
	High-severity fire.
Loss of native hardwoods along the stream that would help reduce erosion and turbidity	Increased temperatures.
	Increased climatic water deficit.
Desired Outcome: Healthy Soil	
Climate Vulnerability	**Plausible Proximate Cause**
Reduced future input of organic matter into soil and loss of soil organic matter	Increase in climatic water deficit.
	Reduced water availability.
	Lowered water table.
	Decreased hydrological connectivity.
	Lack of late-season water.
Herbivory and soil compaction from livestock	Potential increase in the timing and duration of cattle grazing.
	Potential increased demand for cattle grazing.
Increased decomposition of organic matter and soil volatilization	Increase in climatic water deficit.
	Increase in temperature.
	Extreme drought.

Desired Outcome: Meadow Plant Species	
Climate Vulnerability	**Plausible Proximate Cause**
Loss of aspen on edge of meadow and edge habitat	Conifer encroachment.
	High-severity fire.
	Increased herbivory.
Re-encroachment of fuels (lodgepole pine, shrubs) on meadow edge	Novel temperature and precipitation conditions maintain or increase habitat suitability for lodgepole pine.
Meadow type conversion to more xeric community	Increased likelihood of channel degradation and incision dropping water table.
	Decreased runoff resulting in decreased hydrological connectivity.
	Change in vegetation or soil state results in reduced infiltration rate.
Loss of native wetland-associated plants and wet meadow obligates, and increase in forbs and drier plant types	Novel temperature and precipitation conditions outside of ecological tolerances of some species.
	Reduced water availability and lack of late-season water.
	Lowered water table.
	Increased climatic water deficit in meadow.
	Extreme drought.
	Increase in timing and duration of cattle grazing.
	Lack of floodplain activation.
	Long-term disturbances from grazing and climate variability stress plant communities.
Parts of meadow too dry for wetland-associated vegetation	Decreased hydrological connectivity.
	Lowered water table.
	Lack of late-season water.
Encroachment of native upland plants	Channel incision resulting in decreased hydrological connectivity and lowered water table.
	Sedimentation following extreme event or wildfire.
	More frequent drought.
	Increased climatic water deficit.
Invasive vegetation outcompetes native wetland and wet meadow vegetation	Novel temperature, precipitation, and disturbance regimes favor invasive species.
	Invasive vegetation from nearby sites invades newly restored site.
	Increased timing and duration of cattle grazing.

Desired Outcome: High Quality Habitat	
Climate Vulnerability	**Plausible Proximate Cause**
Phenological mismatches among hydrology, plants, and animals	Fruit unavailable for birds in late summer; Flowers unavailable when birds are migrating.
	Changes in timing of water availability and plant seed establishment.
	Higher proportion of winter precipitation falling as rain results in consistent earlier peak discharge.
	Change in timing of invertebrate emergence.
Reduced aquatic habitat	Decreased runoff.
	Multi-year droughts.
Amphibians unable to persist	Multi-year droughts.
	Reduced water availability.
Increased competition for thermal refugia	Increase in spring and summer temperatures.
Loss of willows makes habitat unsuitable for bioengineer (beaver, sapsuckers) and other target species	Novel temperature and precipitation conditions outside of ecological tolerances of some *Salix* species.
	Extreme drought.
	Encroaching conifers shade out willows.
	Reduced water availability.
	Lowered water table.
	Decreased hydrological connectivity.
	Lack of late season water.
	Long-term disturbances from grazing and climate variability stress plant communities.
	Competition for vegetation with cattle and increased timing and duration of cattle grazing.
Unsuitable conditions for beaver occupancy	Very high flows following rain-on-snow and heavy summer rain events blow out beaver dams and/or prevent beavers from establishing on site.
Extreme events directly affect target species and their prey	Extreme summer precipitation and heat events cause mortality through direct exposure.
Edge habitat reduced or lost	Conifer encroachment/re-encroachment.
	High severity fire.
Loss of prey base	Novel temperature and precipitation conditions of ecological tolerances of prey species (e.g., voles) and their habitat.
	Phenological mismatches among hydrology, plants, and animals.

Appendix C: Climate-Smart Actions to Address Vulnerabilities

The following tables list Point Blue's climate-smart principles and examples of associated climate-smart actions linked to desired meadow outcomes.

Principle: Build in ecological insurance		Desired meadow outcomes: Functional meadow hydrology	Good water quality	Healthy soil	Meadow-associated plant species	High quality habitat
Climate-smart actions	Promote beaver occupancy.	✓	✓	✓	✓	✓
	Install beaver dam analog (BDA) posts.	✓	✓	✓	✓	✓
	Encourage multi-thread (anastomosing) channel system that has the ability to adjust naturally to future changes in flow conditions.	✓	✓	✓		
	For pond and plug method, ensure upstream edge of ponds do not concentrate flow.	✓	✓			
	Plant sedge mats, willows, and other riparian shrubs along stream banks for stabilization and to shade the stream.	✓	✓			
	Plant sedge mats along areas of bare dirt after restoration.	✓	✓			
	Encourage regeneration of dense sedge mats to inhibit lodgepole regeneration.	✓			✓	✓
	Plant shrubs along channel and meadow edges and other moisture gradients to increase the number of months fruits and flowers are available.				✓	✓
	Strategically plant willows to promote large clumps of dense foliage with diverse plant understories near water.				✓	✓
	Plant full diversity of riparian deciduous shrubs that occur in the vicinity.				✓	✓

Principle: Build evolutionary resilience		**Desired meadow outcomes**				
		Functional meadow hydrology	**Good water quality**	**Healthy soil**	**Meadow-associated plant species**	**High quality habitat**
Climate-smart actions	Diversify species composition of plantings.				✓	✓
	Source species for plantings from areas lower in the watershed that are warmer and drier.				✓	✓
	Plant large numbers of willows cuttings from all willow species in the meadow.				✓	✓
	Identify and plant more drought-tolerant species.				✓	✓
	Select vegetation palette that favors strong native early colonizers and that compete with invasive species.				✓	✓

Principle: Consider the broader context		**Desired meadow outcomes**				
		Functional meadow hydrology	**Good water quality**	**Healthy soil**	**Meadow-associated plant species**	**High quality habitat**
Climate-smart actions	Decommission spur roads and add gates for other unmarked roads to reduce use of off-road vehicles in the meadow.	✓	✓	✓	✓	✓
	Participate in coordinated watershed management and restoration efforts to improve fire resiliency, maintain and enhance flows, reduce sediment inputs, and increase connectivity.	✓	✓	✓	✓	✓
	Coordinate and work with relevant agencies and landowners to decommission or improve road conditions.	✓	✓			✓
	Work with adjacent property owners to achieve desired outcomes and reduce outside stressors.	✓	✓	✓	✓	✓
	Install fuel breaks to withstand extreme future fire weather.	✓	✓	✓	✓	✓
	Temporarily or permanently close grazing allotment.	✓	✓	✓	✓	✓
	Fence riparian zone from cattle.	✓	✓	✓	✓	✓
	Install cattle exclosures around willows and other sensitive riparian shrubs and trees.				✓	✓
	Provide off-channel water and salt for cattle.	✓	✓	✓	✓	✓

Principle: Monitor and experiment		Desired meadow outcomes: **Functional meadow hydrology**	**Good water quality**	**Healthy soil**	**Meadow-associated plant species**	**High quality habitat**
Climate-smart actions	Use a phased revegetation approach in response to site conditions.				✓	
	Experiment with different invasive species removal approaches.	✓	✓	✓	✓	✓
	Develop and implement adaptive management and monitoring plan for wetland plants, soil, hydrology, target species, and/or invasive species with triggers for management action.	✓	✓	✓	✓	✓
	Develop and implement adaptive management and monitoring plan for cattle grazing that focuses on achieving desired ecological outcomes with triggers for management actions.	✓	✓	✓	✓	✓
	Develop and implement monitoring throughout the watershed.	✓	✓	✓	✓	✓