

Forecasting the Response of Terrestrial Habitats to Climate Change in the Northern Sierra:

Climate Adaptation Strategies for the Northern Sierra Partnership



At-risk aspen–mixed conifer stands, Independence Lake. (photo: Michael Conner/TNC)

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May 2011

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1 Introduction

1.1 The Northern Sierra Partnership

The Northern Sierra Partnership (NSP) is an alliance of organizations committed to protecting the most important lands and waters in the northern Sierra Nevada. The Partnership is comprised of the Feather River Land Trust (FRLT), Sierra Business Council (SBC), Truckee Donner Land Trust (TDLT), the Trust for Public Land (TPL), and The Nature Conservancy (TNC). The Partnership has identified, and is working in, priority areas on both public and private lands (Figure 1-1).

1.2 Conservation Context

The NSP region is home to exceptional natural, cultural, and recreational resources of statewide and global significance. The natural services derived from the mountain valleys, river corridors, and northern conifer forests are crucial to the future of California and Nevada residents and communities. Its rivers provide 60% of California developed water supply, and also support the Nevada cities of Reno and Sparks. Its forest systems are reservoirs of carbon, and its wetlands are home to the greatest diversity and abundance of bird life in the Sierra Nevada. These resources face colliding threats from inappropriate development, stand-replacing wildfire, invasive species, and climate change.

In terms of ownership and stakeholders, over 66% of the five million acre project area falls on public land (Figure 1-1). The public land is owned and managed by the US Forest Service (USFS)(62% of the project area), the Bureau of Land Management (BLM)(3%), and other state and federal agencies (1%). However, only 7% of the project area is managed explicitly for the protection of biodiversity (e.g., wilderness areas, parks, wildlife preserves). Approximately 4% of the area is water, leaving the remaining 29% in private ownership. After well over a decade of conservation action, the organizations of the Northern Sierra Partnership have conserved 101,000 acres of private lands (1% of total area) through a combination of fee title acquisition and conservation easements.

1.1 Climate Adaptation Assessment Components and Goals

The Northern Sierra captures a substantial portion of diversity in species, habitats and physical environments of the greater Sierra Nevada ecoregion. The Northern Sierra Nevada supports endemic plants, butterflies, amphibians, and fishes. The natural habitats of the Northern Sierra include red fir forest, montane meadows, riparian corridors, and aspen groves. The physical environment across the Northern Sierra shows marked variation in topography, elevation, soils, slope, precipitation, and temperature.

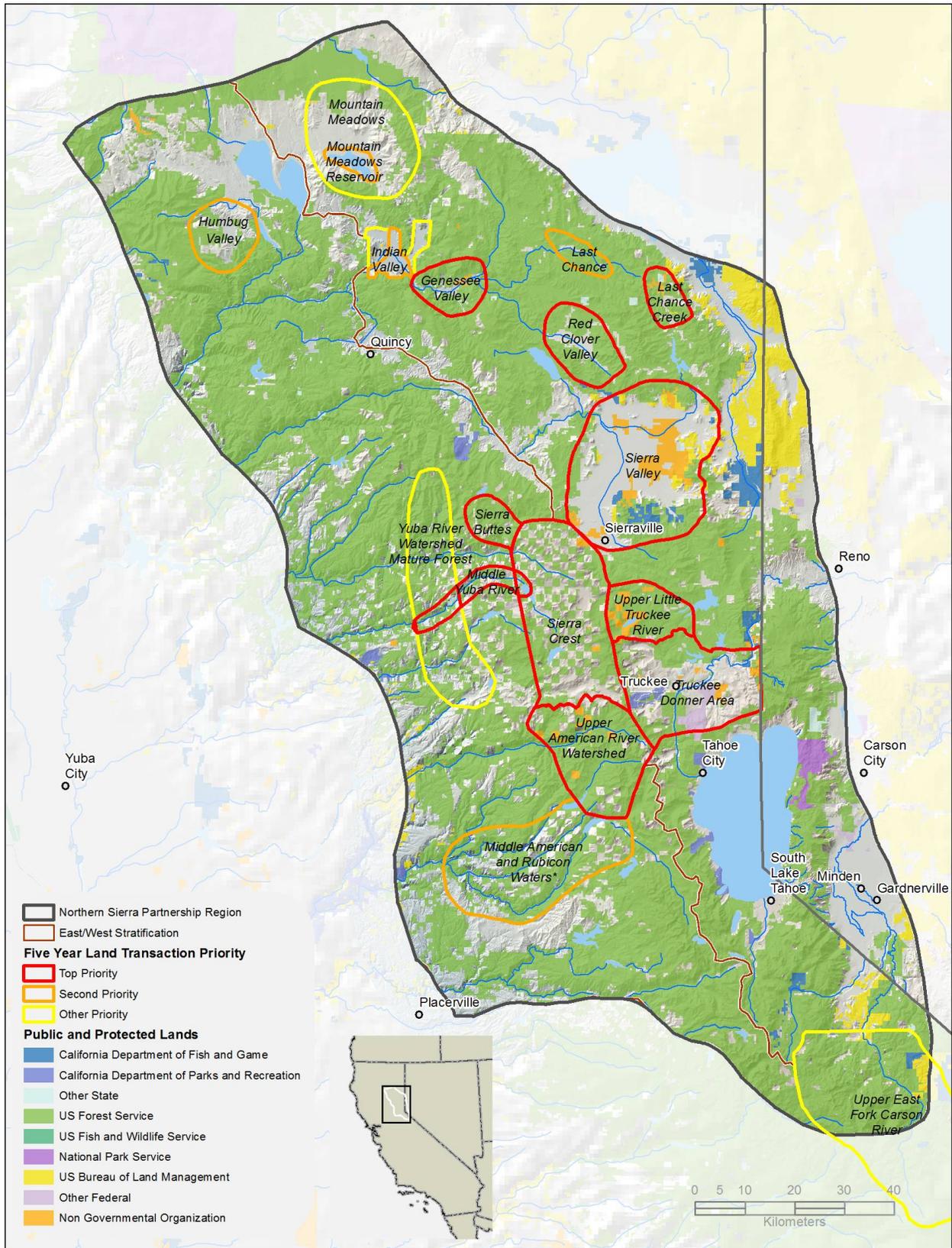
This report integrates climate projections, forecasts of the response of major habitat types, and management simulations to determine: 1) where the northern Sierra's habitats may be at greatest

risk from projected future climate changes, and 2) what conservation strategies might be most cost-effective for reducing or adapting to climate risks for selected at-risk ecosystems.

This assessment takes a two-part approach to evaluate what climate change means for the long-term protection of important lands and waters in the region. The first part, Section 2, tries to inform ‘where to work’ on climate adaptation in the project area. We employ a traditional gap analysis approach (Scott, 1993) to assess the degree to which the Partnership’s existing priority areas are capable of meeting current conservation goals under projected future climate scenarios. To evaluate the potential resilience of existing priority areas in the future, we map landscape features expected to promote cooler temperatures and enhance climate adaptation (e.g., north facing slopes, perennial water sources), and we derive future forecasts for each habitat type to identify those areas that are most likely to remain hospitable under future climate change scenarios. By comparing how both landscape features and potential climate refugia are distributed, inside versus outside of existing priority areas, we propose new ranks of current priority landscapes, and identify potential future land acquisitions, in light of climate adaptation.

The second part, Section 3, tries to inform ‘what to do’ for climate adaptation in those portions of the project area that contain vegetation types that are highly at-risk from climate change. Our approach experiments with novel and extensive modifications to an existing public land management tool, the Vegetation Dynamics Development Tool (**VDDT**), to incorporate climate change. Focusing on vegetation types that depart most greatly from their desired range of variability under a climate change scenario, this part evaluates current and future stresses on existing vegetation systems (e.g., mortality, invasion) and then evaluates existing NSP strategies (e.g., stream and meadow restoration, forest thinning, prescribed fire) in terms of cost-benefits for reducing ecosystem degradation and adapting to the risks of climate change. While Sections 2 and 3 detail independent methods and findings, Section 4 synthesizes conclusions and recommendations for the entire climate assessment.

Figure 1-1. Northern Sierra Partnership Region



2 Evaluation of Existing Priority Areas

2.1 Climate Adaptation Planning Methods

The Partnership has defined priority areas for conservation action, and assigned priority ranking for land acquisition in each priority area (see Figure 1-1). This study examines whether the explicit consideration of climate change in relation to major habitat types would alter these priority rankings. To do this, we first determined historical trends and the projected changes in climate for the entire project area. We then determined how well the current priority areas capture the diversity of major habitat types in the project area. For the purpose of this project, we classified major habitat types as Biophysical Settings (hereafter, **BpS**).

Next, we mapped landscape features that are expected to remain cool and wet in the face of climate change. Such features include springs, seeps, north-facing slopes, and river corridors. We defined such landscape features as climatic microrefugia because they may provide refuge to species from the adverse impacts of a changing climate. We determined which priority areas have a high density of microrefugia and thus are more likely to be resilient to climate change.

Finally, we modeled the distribution of major vegetation types to determine the landscape areas most likely to be stressed from climate change, as well as the landscape areas where climatic conditions may remain favorable to major habitat types. Those locations where major habitat types are forecast to persist are defined as Biophysical Setting refugia (henceforth, **BpS refugia**). We calculated the amount of BpS refugia in each priority area, assuming that these will be the areas that provide the most stability as the climate changes.

We combined all of this information to generate an alternative ranking for the priority areas, and then compared with the current priority areas. This information is intended to provide insights about climate change impacts and resilience, in order to help inform future conservation decisions. Section 2.1.1 outlines the specific methods we used to evaluate existing priority areas, and Section 2.2 presents the results of these methods.

2.1.1 Climate Forecast Methods

In order to best determine how to adapt to climate change, we need to understand the historical climate for an area, the recent observed trends, and the projected changes in climate. The historical data is based on direct observations from weather stations over time. These observations are used in a computer model to generate estimates for areas lacking climate stations based on topography, elevation, and other relevant features. Future climate projections are based on computer models that model the earth's atmosphere and ocean for a given trajectory of greenhouse gas emissions. These models are called general circulation models (**GCMs**). When combined, the historical trends and future projections can show how much different the future climate is likely to be from the observed climate.

While other studies have summarized projected climate change for this general area, this is the first summary we know of that includes both historical and future projections from an ensemble of GCMs that is specifically tailored to the Partnership study area.

2.1.1.1 Historical Climate Observations

We calculated the observed climatic averages and trends with the historical climatology developed using the PRISM (Parameter-elevation Relationships on Independent Slopes Model) interpolation method (Daly et al. 2008)¹. These data provide estimates of minimum temperature, maximum temperature, and precipitation for each 30-arcsec (~800 meter) grid cell in the conterminous United States for each month from 1895 to 2007. We selected the 1961-1990 period as representative of the base climate before significant influences of anthropogenic climate change in order to calculate the magnitude of the projected climate change in the 21st Century.

2.1.1.2 Future Climate Projections

To estimate future climate for the NSP project area, we downscaled projections of future climate from an ensemble of General Circulation Models (GCMs) run to support the International Panel on Climate Change's (IPCC) Fourth Assessment Report archived in the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project (CMIP) phase 3 multi-model dataset (Table 2-1). We compiled monthly and annual climate data modeled from 11 GCMs for two 20-year time periods (2046-2065 or mid 21st Century, and 2081-2100 or end of the 21st Century). While all the GCMs in the CMIP multi-model dataset project changes in average temperature and precipitation, only 11 GCMs include forecasts of minimum temperature and maximum temperature for the A2 emissions scenario. Data on maximum and minimum temperature are important for species distribution modeling, so we focused our analysis on these 11 GCMs. We selected the A2 emissions scenario (Nakicenovic and Swart 2000) because of the three emissions scenarios analyzed by most modeling groups, the A2 scenario is the closest to the observed trends since 2000 (Raupach et al. 2007). For the GCMs that provided multiple realizations, we averaged the results. We then downscaled the future climate projections to the 30-arcsec (~800m) resolution of the PRISM historical climate data using the change factor approach as described in Klausmeyer and Shaw (2009).

¹ The original data were released in 2008; data for 2002-2006 were updated in March 2009.

Table 2-1. General Circulation Models (GCM) used in this analysis. Full documentation can be found here: http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php. We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modeling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. The U.S. Department of Energy's Office of Science provides support for this dataset.

Model Name	Country	Center Name
CGCM3.1(T47)	Canada	Canadian Centre for Climate Modeling & Analysis
CNRM-CM3	France	Météo-France / Centre National de Recherches Météorologiques
CSIRO-Mk3.5	Australia	CSIRO Atmospheric Research
CSIRO-Mk3.0	Australia	CSIRO Atmospheric Research
GFDL-CM2.0	USA	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory
GFDL-CM2.1	USA	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory
IPSL-CM4	France	Institut Pierre Simon Laplace
ECHO-G	Germany & Korea	Meteorological Institute of the University of Bonn (MIUB), Meteorological Research Institute of KMA (METRI), and Model and Data group (M&D)
ECHAM5/MPI-OM	Germany	Max Planck Institute for Meteorology
MRI-CGCM2.3.2	Japan	Meteorological Research Institute
MIROC3.2 (medres)	Japan	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)

2.1.2 Mapping of Current Vegetation

To map current vegetation we utilized a new classification approach called “biophysical settings” (BpS). The LANDFIRE program (<http://gisdata.usgs.net/website/landfire/>) provided the underlying vegetation pattern from which we derived the BpS classifications, and we also included minor refinements with more accurate fine-scale vegetation surveys. Biophysical settings describe the expected dominant vegetation in an area prior to European settlement, based upon what is known of today’s vegetation and physical environment, as well as historical disturbance regimes. Biophysical settings are in essence the major habitat types of the Northern Sierra Nevada and are identified by the dominant plant species present in each habitat type.

For details of the vegetation data processing see Appendix A.

2.1.3 Identification of Current Microrefugia

Microrefugia are locations on the landscape that are expected to retain cooler temperatures and higher water availability, compared to other locations, as climate change gradually warms and dries the Sierra Nevada in the future. Microrefugia may be more likely to provide the physical environmental conditions required by some plants and animals in the Sierra Nevada under a changing climate.

There is evidence that species have utilized microclimatic refugia in the past in response to dramatic climate changes between glacial and interglacial periods, and it is likely that microclimatic refugia will play a role in preserving species on a landscape in the current period of anthropogenic climate change (Dobrowski 2010). Features of the landscape can provide enduring microclimatic refugia to a hotter and potentially drier future. For the Northern Sierra, these features include:

- Cold air drainages. As the climate warms, species adapted to cold conditions such as frost may be outcompeted by more warm-adapted species. On cool still nights in mountainous areas, dense cold air drains down slope and pools in valleys. Areas with cold air pooling may continue to support cold-adapted species or meet the ecological requirements of species dispersing to cold air drainages as the surrounding landscape warms (Dobrowski 2010).
- North-facing and shaded slopes. High maximum temperatures in a warmer climate may stress species adapted to current conditions. Maximum temperatures on sunny days are highly dependent on the exposure and shading provided by the local topography, with steep north facing and shaded slopes receiving much less sun and reaching lower maximum temperatures. Evaporative demand is also lower on north-facing slopes, increasing soil moisture and water availability. These slopes may provide a refuge to species in comparison to flat and south facing slopes (Dobrowski 2010).
- Seeps and Springs. If the climate becomes warmer and/or precipitation becomes more variable while shifting to more rain-dominated precipitation during cold months, current surface flows may dry up earlier in the summer. Seeps and springs discharge water that has moved through bedrock and alluvium for decades to centuries so they are more likely to maintain steady flows as the climate becomes more variable. Areas on the landscape with a higher density of these features are more likely to provide refuge to plants and animals if the climate becomes drier and more variable.
- Riparian Corridors. Riparian corridors can provide multiple microclimatic refugia benefits because they collect water and cold air from the surrounding landscape, and they are often more shaded than exposed slopes (Seavy et al. 2009). Functionally, riparian areas serve as movement corridors for wildlife, aquatic biota, and nutrients serving a key role to adaptation (Wilme et al. 2006).

In order to locate these microclimatic refugia features in the Northern Sierra, we utilized the following methods and data sources:

- Cold air drainages: While there have been some recent papers describing methods to map cold air drainages, these methods require fine temporal and spatial scale temperature records for testing and calibration (Chung et al. 2006; Lundquist et al. 2008). These data were not available for this analysis, so we used an existing map of areas that are lower than the surrounding areas called “drainage channels” from the U.S. Geological Survey to identify potential locations for cold air drainage (Sayre et al. 2009). Sayre et al. (2009) identified drainage channels by calculating the topographic position index from ~30-meter National Elevation Dataset (United States Geological Survey (USGS) 2008). The topographic position index compares the elevation at a point to the mean elevation in a 1-kilometer² circle around the point (Weiss 2001). In areas where this value is negative, the elevation is lower than the surrounding landscape indicating a local valley. These values were standardized using the standard deviation of the elevation in the 1-kilometer² circle, and the lowest topographic position index values were assigned to the drainage channel class to remove some of the smaller localized valleys. This method does not take into account the size of the drainage or any potential blockages to cold air flow on still nights, so it should be regarded as a first-order approximation of cold air drainages.
- North-facing and shaded slopes: We calculated the annual total incoming solar radiation using the ~30-meter National Elevation Dataset (USGS 2008) and the solar insolation tools in ArcGIS. We then broke the landscape into four quartiles and chose the quartile with the lowest insolation (receiving less than 1,395 kilowatts hours per square meter per year) to identify the north-facing and shaded slopes.
- Seeps and Springs. We identified all of the seeps and springs from the National Hydrology Dataset. In order to fill in areas with missing data, we combined the seeps and springs from both the 1:100,000 scale National Hydrology Dataset Plus v1.1 (US EPA and USGS 2005) and 1:24,000 scale National Hydrology Datasets (USGS 2009).
- Riparian Corridors. We identified all second order perennial streams identified in the National Hydrology Dataset Plus v1.1 (US EPA and USGS 2005).

2.1.4 Forecasts of Vegetation Change Using Surrogate Plant Species

We ran models to forecast how vegetation may be affected by climate change in the Northern Sierra Nevada. We identified a tree or shrub species to serve as a surrogate for most of the BpS habitat types in the project area based on the dominant plant species for that habitat type. We then used the historical and projected future climate data and a method called species distribution modeling to map the climatically suitable conditions for the surrogate species found in the study area. This method provides us with a map of the climatically suitable conditions for species in the base time period (1960-1990) as

well as in the future time period (2045-2065). In some cases, these two maps overlap, indicating the area may provide suitable conditions for the species as the climate changes.

BpS refugia are locations where current and future maps of climate suitability overlap. BpS refugia are likely to be more stable in terms of species composition as the climate changes. In the areas where the BpS habitat is currently found, but it is not forecast to be climatically suitable in the future, we assume this will be an area of stress for the surrogate tree or shrub species. As disease, fire, or other disturbances remove the existing vegetation, these areas may transition to another vegetation type. The fate of these areas is more uncertain, so we highlight them as a climate change adaptation feature in this analysis.

2.1.4.1 Biophysical Settings (BpS) Defined by Surrogate Species

The Nature Conservancy's California Climate Adaptation Science Team has generated maps of historical and future climate suitability for most species of trees and shrubs considered to be ecological dominants of the state's terrestrial wildlife habitat types, based upon the California Wildlife Habitat Relationships (**CWHR**) classification system (Mayer and Laudenslayer 1988). While these habitat forecasts were explicitly developed for species, the Partnership required forecasts for biophysical settings (BpS) to provide more relevant information to public land managers in the northern Sierra. We drew upon expert knowledge of vegetation patterns to develop a crosswalk from surrogate species to BpS types in the project area (Hugh Safford, Louis Provencher and Greg Low; pers. comm.)(Table 2-2).

Table 2-2. Biophysical settings (BpS) and the associated surrogate species chosen for forecasting in this climate adaptation assessment.

Biophysical Settings (BpS)	Surrogate Species
Subalpine Forests	
Lodgepole Pine - Dry	lodgepole pine
Lodgepole Pine - Wet	lodgepole pine
Red Fir - Western White Pine	red fir
Red Fir - White Fir	red fir
Subalpine Woodland	mountain hemlock
Mid-Elevation Forests	
Aspen-Mixed Conifer Forest	aspen
California Oak-Pine Forest	CA black oak
Mixed Conifer - Mesic	white fir
Ponderosa Pine - Mixed Conifer	ponderosa pine
Yellow Pine	jeffrey pine
Low-Elevation Forests	
Blue Oak–Foothill Pine Woodland	blue oak
Xeric Shrublands	
Montane Chaparral	greenleaf manzanita
Mid-Elevation Shrublands & Woodlands	
Aspen Woodland	aspen
Big Sagebrush Shrubland	big sagebrush
Curleaf Mountain Mahogany	curleaf mountain mahogany
Low Sagebrush	gray low sagebrush
Montane Sagebrush Steppe	mountain big sagebrush
Pinyon Juniper	singleleaf pinyon

In this report, we limit all BpS forecasts to only those areas where the BpS is mapped. If a BpS is not known to occur in an area, we do not consider associated forecasts. For example, as alluded to in Table 2-4, species forecasts for blue oak (*Quercus douglasii*) were used as a surrogate to generate forecasts for blue oak–foothill pine woodlands. Blue oak forecasts were only considered if they fell within areas where blue oak–foothill pine woodlands are known to occur today. For each BpS, current distributions are partitioned into those areas forecasted to be resilient to projected changes in future climate (i.e., BpS refugia) versus those areas forecasted to be at-risk (i.e., climate stress).

For this exercise, BpS refugia are considered priority areas for conservation, particularly for large contiguous areas, because they may offer resilience to expected climatic threats and may increase the probability that major habitat types will persist over decades. In contrast, climate stress zones may identify geographies that are most vulnerable to climate change, as well as potential areas where monitoring programs might look for ecological thresholds and tipping points.

The plant species forecasts designed to represent BpS habitat types assess potential climate impacts from multiple (n=11) projected future climates simultaneously (description of climate data in Sections 2.1 - 2.2). Observation data used to infer species' climatic preferences include a compilation of statewide field surveys (Hannah et al. 2008), supplemented by herbarium specimen records from the California Consortium of Herbaria (<http://ucjeps.berkeley.edu/consortium/index.html>). All species distribution models were derived using default settings in Maxent (<http://www.cs.princeton.edu/~schapire/maxent/>), a method shown to model species distributions well in comparative studies (Elith et al. 2006). To summarize species forecasts herein, we use an ensemble approach that treats all futures as equally likely (Araujo and New 2006). For each species forecast, we overlay models of current and future climate suitability, resulting in each of 3 potential categories: (1) areas suitable both today and in the future (i.e., BpS refugia), (2) areas suitable today, but not in the future (i.e., climate stress) or (2) areas suitable in the future, but not today (i.e., expansion). To gauge uncertainty in species forecasts, we distinguish areas where forecasts are based upon high consensus ($\geq 80\%$ model agreement) versus moderate consensus (60-80% model agreement).

2.1.4.2 Biophysical Transition Rates

In order to support the dynamic BpS modeling presented in Section 3, we used the results from our BpS forecasts to estimate the rate at which each BpS type may transition to another BpS type as a result of the stresses associated with climate change. To approximate potential transition rates for each BpS type, we first calculated the percent current distribution which is modeled as climate stressed over a future ~80 year interval (1961-1990 to 2045-2065). To forecast annual transition rates, we simply divided % area forecasted to be stressed by the total years considered. For example, if BpS projections suggest 20% of the current distribution may be stressed by climate change over an 80 year interval, then the annual transition rate was calculated to be 0.25% loss per year. The constancy of this rate over 80 years was the simplest assumption in the absence of an alternative assumption (i.e., decreasing or increasing rate of stress) supported by data. For more details on the application of this transition rate, see the forecasting risk to ecosystems component (Section 3).

2.1.5 Evaluation of Current Priority Landscapes

2.1.5.1 Criteria for Existing Priority Landscapes

The current set of NSP priority areas captures the top landscape priorities for each participating organization in the Partnership. The NSP seeks to understand how well its current portfolio achieves landscape conservation goals in light of climate change.

2.1.5.2 Gap Analysis of Adaptation Factors

Three adaptation factors are explored here in a gap analysis to evaluate the suitability of priority areas for major habitat types under a changing climate. The first adaptation factor is the current distribution of major habitat types as mapped through the biophysical settings (BpS) approach. The second factor is climatic microrefugia that are expected to maintain favorable temperatures and water availability under a changing climate. The third factor is the BpS refugia where we expect major habitat types to persist in the future.

A general conservation gap analysis works by determining how much certain conservation elements (species, rare soil, vegetation type, etc) are found within a set of protected areas, and highlighting where representation is low, or, where the conservation “gaps” occur in the protected area network. Rather than species or rare soils, a climate adaptation gap analysis highlights the presence of climate adaptation factors, or factors that would allow existing biota to persist given future climate projections within NSP priority protection areas.

Conservation plans often aim for a minimum level of representation as a goal (e.g., 20% of current extent) to safeguard against loss of any characteristic conservation element in the region. As biodiversity is unevenly distributed (some habitats harbor more total or endemic species), many conservation plans vary the minimum level based on the importance of a given element for overall diversity (e.g., rare elements get a higher goal).

For all three factors considered in the gap analysis, we calculated representation within individual priority areas, representation within all priority areas east versus west of the Sierra crest (to account for the large difference in current climate on each side of the crest), and finally, representation within the entire project boundary (both priority and non-priority). We set a baseline goal of 20% representation in priority areas for all adaptation factors. We then used ratios from these assessments to evaluate how well adaptation features are represented in the current set of NSP priority landscapes.

2.1.5.3 Climate Adaptation Ranking of Priority Landscapes

The Partnership has established five year priorities for land transactions in each of the priority landscapes (Figure 1-1). We wanted to determine how these rankings might be altered to reflect the representation of adaptation factors in each priority landscape. To do this for the current distribution of BpS types, we simply ranked the priority landscapes by the count of unique BpS it contains. We assumed that priority landscapes containing a

higher diversity of BpS today will likely be more resilient to change in the future, because as the climate changes, it is more likely that there will be species present to capitalize on the new conditions if there is a high diversity of species in the priority area now. For microrefugia and BpS refugia, we calculated the percent of each adaptation factor identified within a given priority area relative to the total available on that side of the Sierra Nevada crest. We then summed these percentages for all categories (e.g., north facing slopes microrefugia, ponderosa pine macrorefugia) to rank each priority area in terms of the representation of either microrefugia or BpS refugia. Since larger areas tend to contain more adaptation factors than smaller ones, we normalized (divided) this score by the area of each priority area relative to the size of its side of the study area. The resulting index can be used to rank the priority areas in terms of their density and diversity of microrefugia or BpS refugia.

Finally, we generated a summary score that synthesizes the ranks of the priority landscapes for each adaptation factor. To do this, we calculated the rank for each adaptation factor, then added the ranks together. Based on this analysis, the priority landscapes with the lowest summed ranks are the most important to protect to promote the adaptation of the species in the NSP region.

2.2 Climate Adaptation Key Findings About ‘Where to Work’

2.2.1 Climate Impacts

All of the GCMs analyzed project significant warming in the NSP region by 2050 (see Appendix B for maps and figures of the projected changes). When looking at a 20 year moving average, average annual minimum temperatures generally ranged from between 33.5° and 34.5°F in the region from 1900 to 1990 (Appendix B, Figure B1). Starting in the 1990s, the trend has increased so that the average annual minimum temperature for the 1988-2007 period was almost 36°F. The GCMs project temperatures will continue to increase, with the average annual minimum temperature for the 2046-2065 period ranging from 37° to 39°F (a 3° to 5°F projected increase from pre-1990 temperatures). By the end of the century, the hottest GCM project a 20-year average annual minimum temperature of 41°F. While the recent trends in average annual maximum temperatures are not so pronounced, the projected changes are similar (Appendix B, Figure B2).

While the GCMs all project warming in the future, they do not agree on the sign or magnitude of the projected changes in precipitation (Appendix B, Figure B3). The 20-year moving average of precipitation across the region varied from 36 to 48 inches over the 20th century. Most of the GCM projections for the mid 21st century also fall in this range, although two project significantly wetter conditions reaching 55 inches per year. Compared to the base period of 1961-1990, the majority of models project a drier future, but the projected change is small relative to historical variability. Appendix B also

contains a series of maps showing the spatial patterns of the current climate in relation to the projected climate by the middle and end of the 21st Century.

2.2.2 Evaluation of Conservation Priority Landscapes

2.2.2.1 Representation & Interpretation of Current Vegetation Systems

The Northern Sierra Partnership assessment involves an approximately five million acre landscape that includes 25 major habitat types, called biophysical settings, ranging from sagebrush shrublands to subalpine woodlands and alpine shrublands (Figure 2-1). Five forest systems comprise over 75% of the project area. The largest major habitat type covers approximately 1,100,000 acres, the mesic mixed conifer forest, followed by approximately 900,000 acres of yellow pine and 784,000 acres of ponderosa pine.

In general the level of representation for the ten most extensive BpS habitats is quite high (>20%) across the study area (Figures 2-2, 2-3) with the exception of Ponderosa Pine-Mixed conifer and Big Sagebrush Shrubland. The BpS habitats most poorly represented within priority areas (Figures 2-4 – 2-5) on the west side include Lodgepole Pine-Dry (0%), Blue Oak-Pine Foothill Woodland (3%), Subalpine Meadow (4%), Pinyon-Juniper Woodland (5%) and Alpine Shrubland (5%). Yet, all of these types have less than 5000 acres in the west side of the study area, suggesting they are not widely distributed and may be more common elsewhere in the Sierra or Central Valley foothills. Two types, Alpine Shrubland and Subalpine Meadow are naturally limited but well-protected in existing Wilderness and National Parks in the Sierra, and will likely be strongly affected by warming temperatures. Blue Oak-Foothill Pine woodlands are more common lower in elevation around the Central Valley and as such are not common in the study area. More widely distributed types that fall below 20% on the west side include Ponderosa pine – Mixed conifer (11%), California Montane Riparian (11%), California Mixed Evergreen Forest (11%), and Yellow Pine–East Side (16%). The most extensive area that is missed is the Ponderosa Pine–Mixed Conifer, and as shown on Figure 2-2, this type is widely distributed along the western boundary of the study area. This would be a logical place to add an additional priority area(s) to better meet a minimum goal for representation within the NSP study areas. This BpS is typically found on National Forest lands and private timberlands outside of wilderness areas.

The Ponderosa Pine–Mixed Conifer habitat is also widely distributed on the east side, but falls just short of the 20% minimum, at 19%. A more significant gap is found in the Big Sagebrush Shrubland which is only 10% picked up by priority areas. This is not surprising given the distribution of this type in valley floors and low foothills just west of the major developed areas on the east side, far from the focus of the NSP on the higher elevation forest ecosystems. If there was a goal within the Partnership to have a representative mix of ecosystems within priorities, then this would be one of the first places to expand. Similar types that are poorly represented on the east side include Low

Adapting to Climate Change in the Northern Sierra

sagebrush (2%) and Mixed Salt-Sodic Desert Scrub (3%). Several less common types fall below the 20% cutoff on the east side as well, including Curleaf Mountain Mahogany, Lodgepole Pine–Dry, and Aspen Woodland.

Figure 2-1. Map of Northern Sierra biophysical settings.

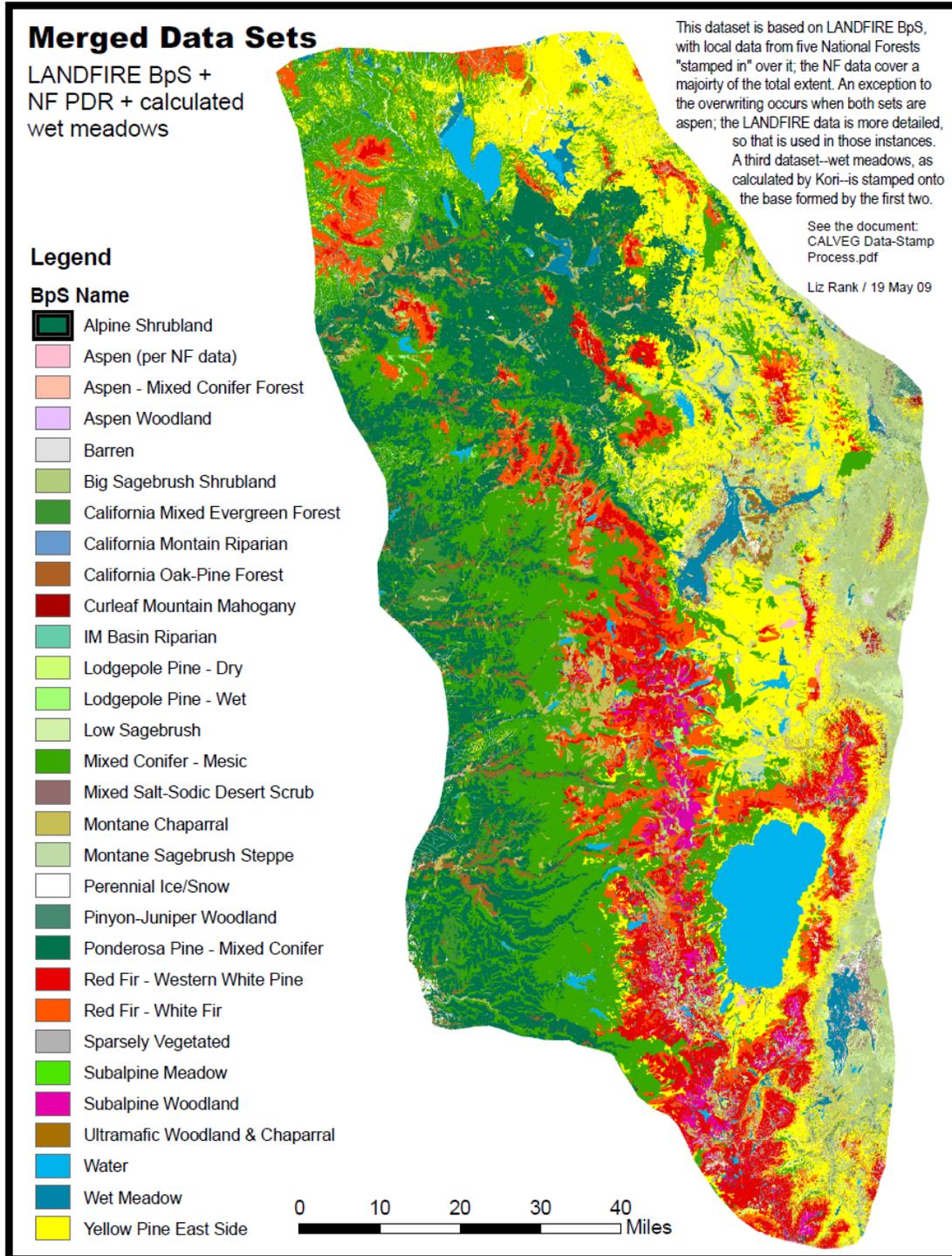


Figure 2-2. Current representation of common biophysical setting (BpS) types (> 40,000 acres in the study area) within NSP priority areas east of the Sierra Nevada crest.

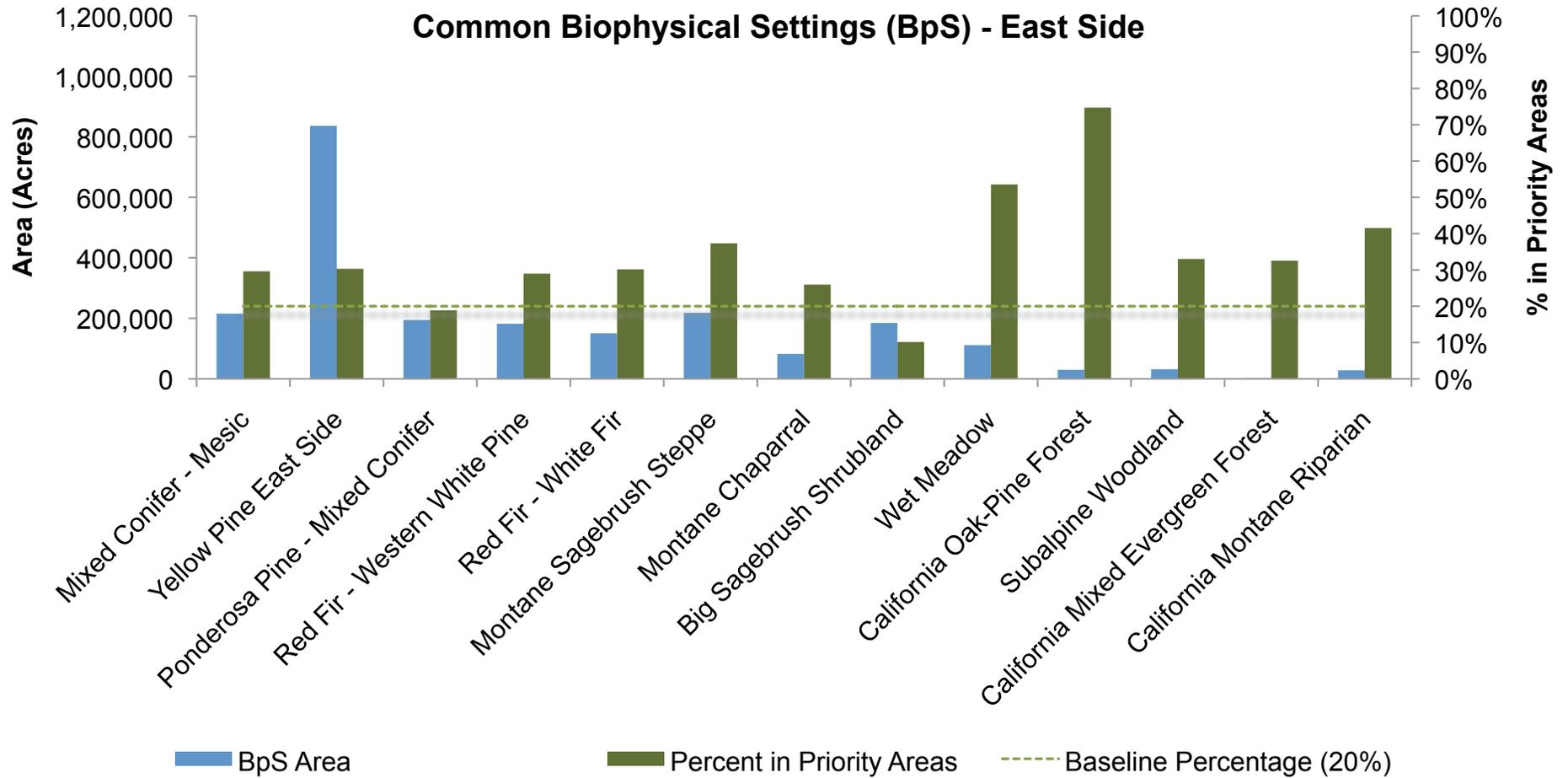


Figure 2-3. Current representation of common biophysical setting (BpS) types (> 40,000 acres in the study area) within NSP priority areas west of the Sierra Nevada crest.

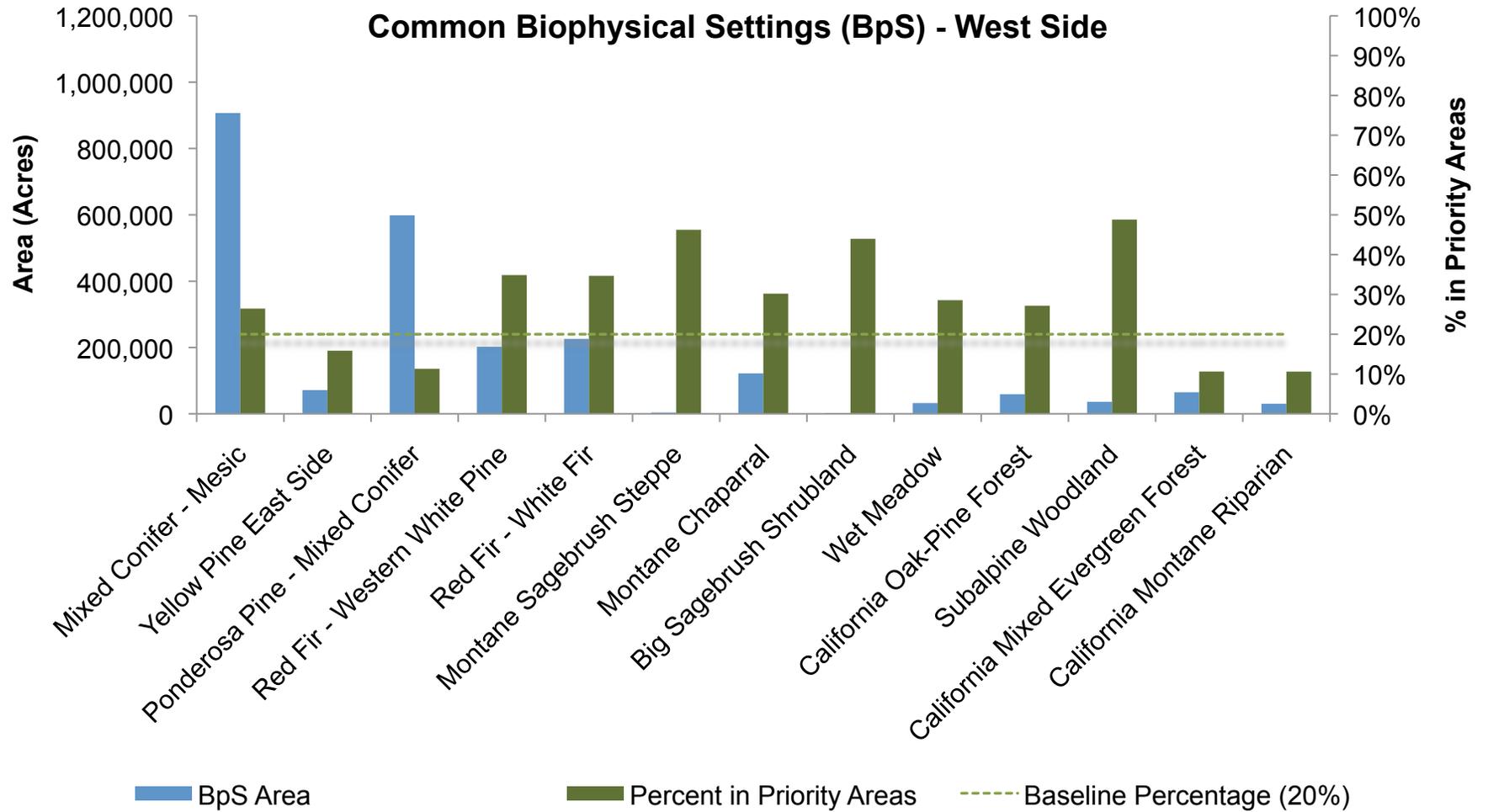


Figure 2-4. Current representation of less common biophysical setting (BpS) types (< 40,000 acres in the study area) within NSP priority areas east of the Sierra Nevada crest.

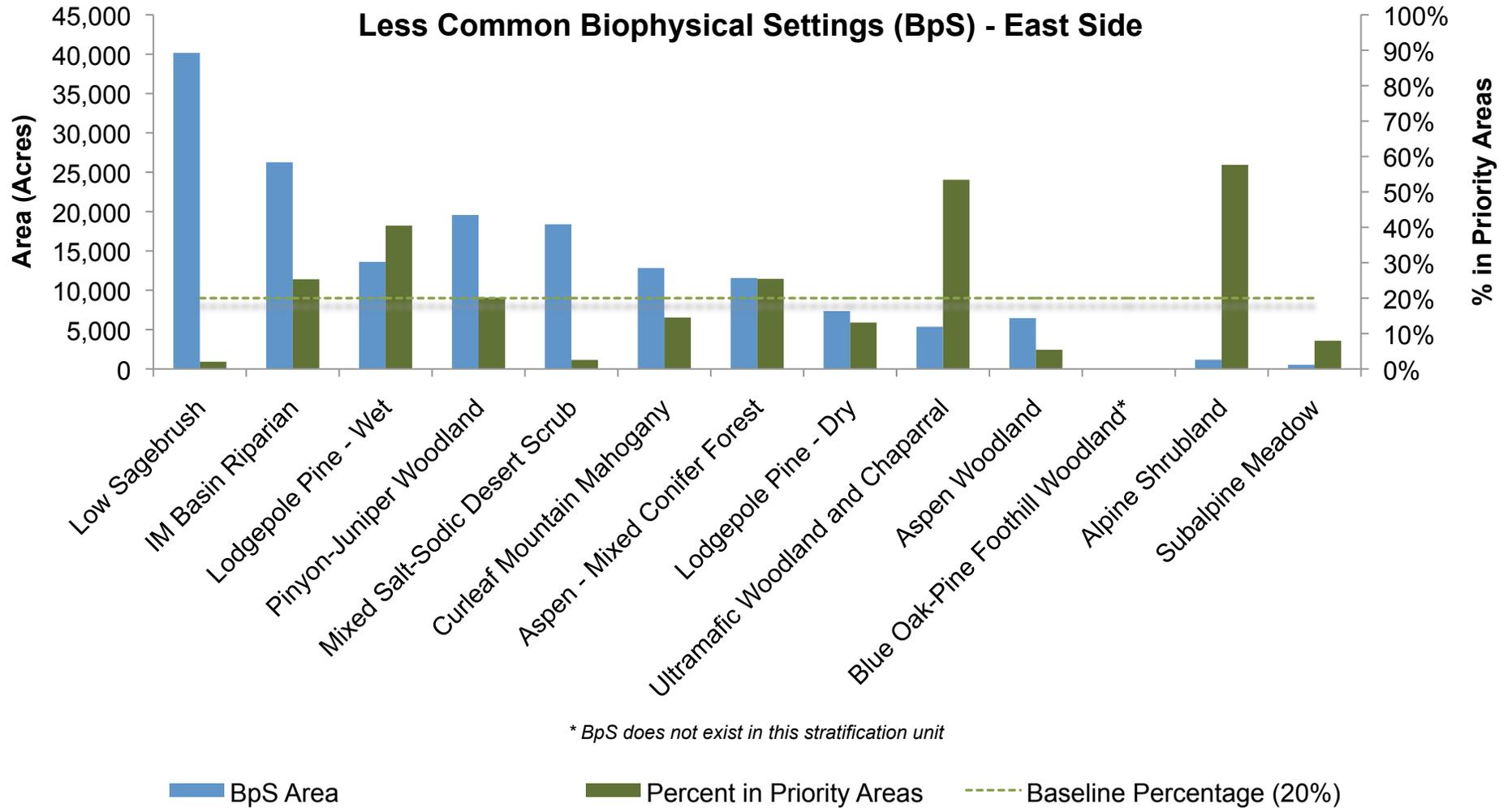


Figure 2-5. Current representation of less common biophysical setting (BpS) types (< 40,000 acres in the study area) within NSP priority areas west of the Sierra Nevada crest.

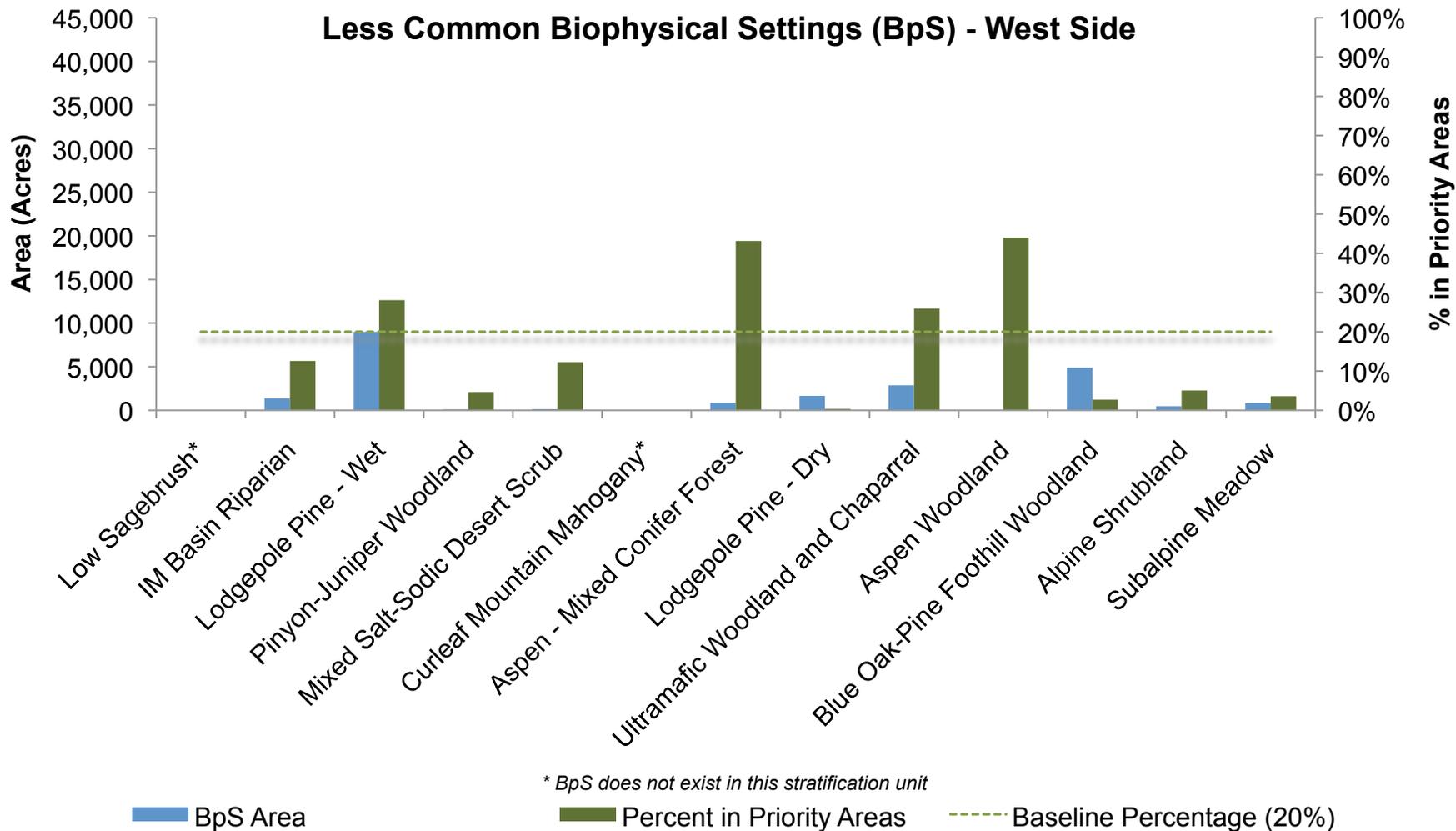


Figure 2-6. Current distribution of under-represented biophysical settings (BpS) within NSP priority areas.

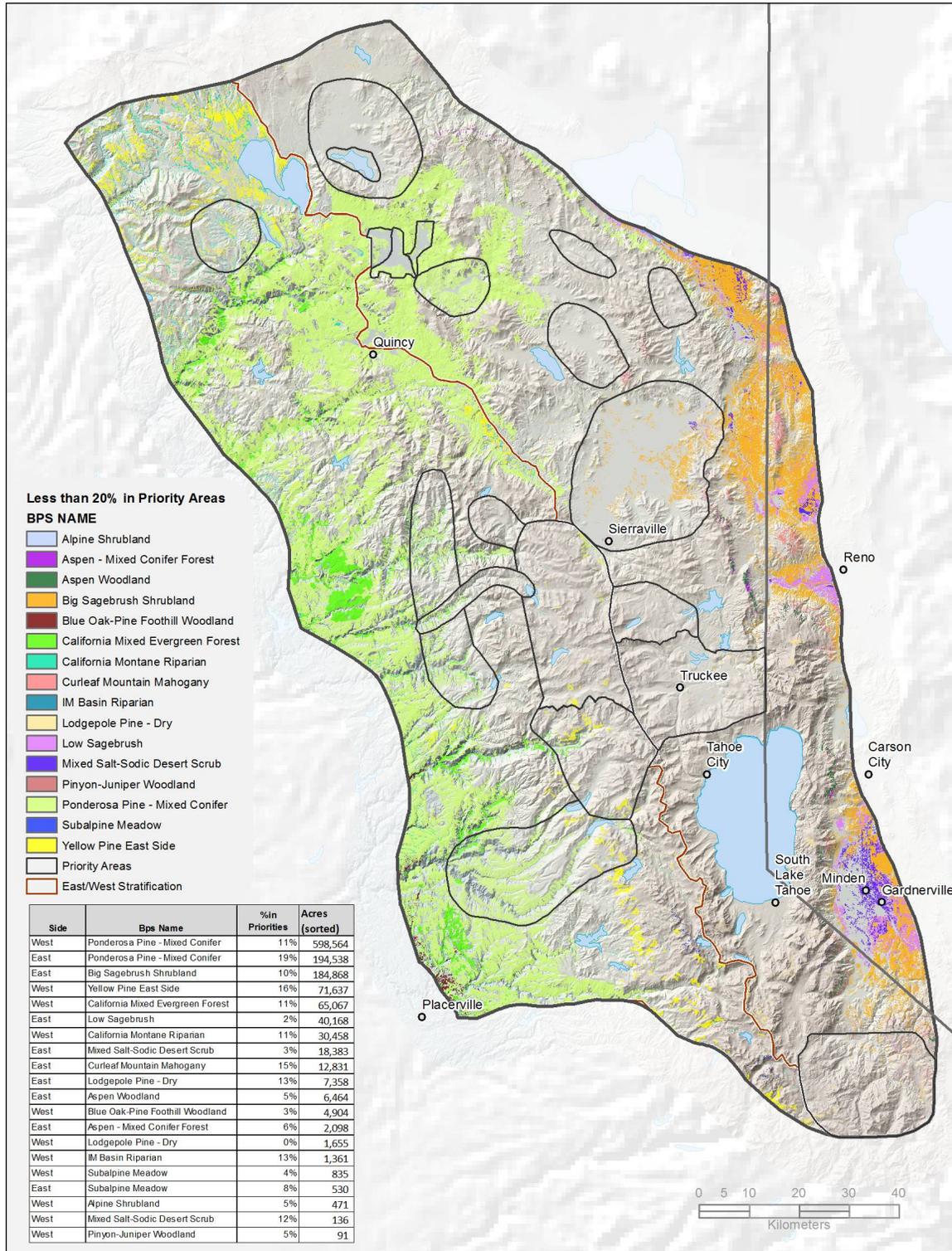


Table 2-3. Diversity of BpS types in each of the 19 NSP priority areas. The Upper East Fork Carson River priority area contains the highest diversity with 28 unique BpS types, followed closely by Truckee Donner Area (26), Sierra Crest (25) and Upper American River Watershed (25). The Last Chance priority area has the lowest diversity with 11 BpS types. This does not suggest that lower ranking sites should not be priority areas, only that such sites include lower diversity of BpS types than others.

Table 2-3 Diversity of BpS types in each Priority Area

Zone	Priority area name	Count of BpS types	Feature rank
East	Upper East Fork Carson River	28	1
East	Truckee Donner Area	26	2
West	Sierra Crest	25	3
West	Upper American River Watershed	25	3
East	Mountain Meadows (rank 3)	23	5
East	Upper Little Truckee River	23	5
East	Sierra Valley	22	7
West	Middle American and Rubicon Waters	20	8
East	Genessee Valley	19	9
East	Red Clover Valley	19	9
West	Sierra Buttes	19	9
West	Humbug Valley	18	12
West	Middle Yuba River	17	13
West	Yuba River Watershed Mature Forest	17	13
East	Last Chance Creek	16	15
East	Indian Valley (rank 2)	15	16
East	Mountain Meadows (rank 2)	15	16
East	Indian Valley (rank 3)	14	18
East	Last Chance	11	19

2.2.2.2 Representation & Interpretation of Existing Microrefugia

The Northern Sierra Partnership study area contains a high density of microrefugia (Figure 2-7), including over 775,000 acres of cold air drainages, 1.2 million acres of north-facing and shaded slopes, 2,790 seeps and springs, and over 3,000 miles of river corridors. The higher elevation areas contain relatively more cold air drainages and seeps and springs, while the steep slopes associated with the major drainages on the west side

and the escarpments on the east side contain the majority of the north-facing and shaded slopes. River corridors are distributed throughout the study area.

The existing priority areas include a good representation of these microrefugia features on both the east and west side of the Sierra Nevada crest. As shown in Figure 2-8, the priority areas on the east side of the study area contain 39% of the river corridors, 36% of the seeps and springs, 29% of the cold air drainages, and 28% of the north-facing and shaded slopes. As shown in Figure 2-9, the priority areas on the west side of the study area contain 24% of the river corridors, 22% of the seeps and springs, 23% of the cold air drainages, and 22% of the north-facing and shaded slopes. While in general the representation percentages are a little lower in the west side, all of the features are better represented than our 20% baseline on both sides of the Sierra Nevada crest.

Figure 2-7 shows the percentage of the total microrefugia features represented in each priority area. In general, the microrefugia features are well distributed throughout the study area, but some priority areas contain a higher percentage of a given feature. The Upper East Fork Carson River priority area contains the highest percentage (6.4%) of the cold air drainage area and the highest percentage (17.6%) of the seeps and springs. The Middle American and Rubicon Waters priority area contains the highest percentage (7.6%) of the north-facing and shaded slopes, and the Sierra Valley contains the highest percentage (12.3%) of river corridor length. After summing the percentages and normalizing by area, the Upper East Fork Carson River has the most diversity and highest density of microrefugia features, followed by Genessee Valley, Indian Valley, and the Middle American and Rubicon Waters.

Figure 2-7. Current distribution of all microrefugia within NSP study area.

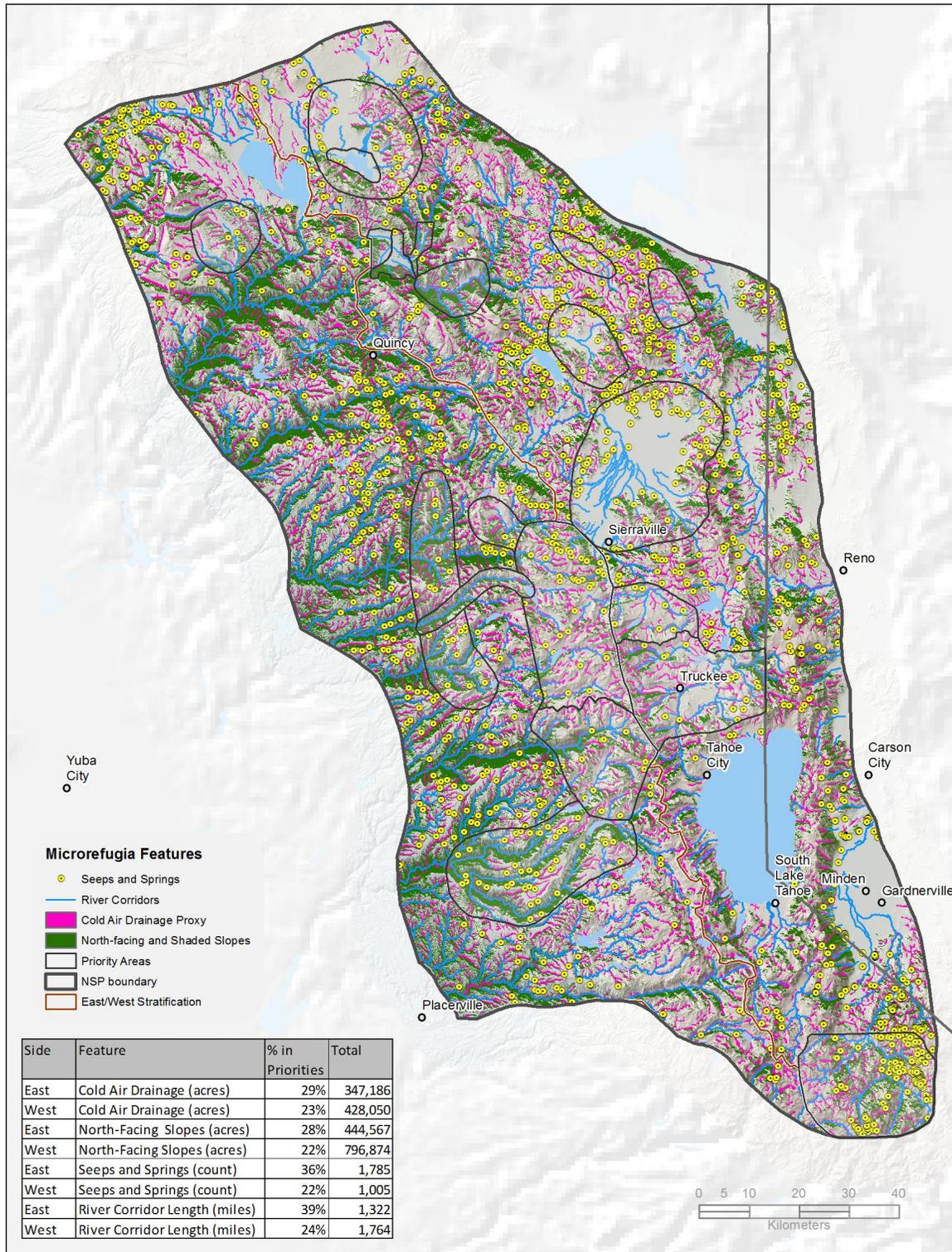


Figure 2-8. Current representation of microrefugia within NSP priority areas east of the Sierra Nevada crest.

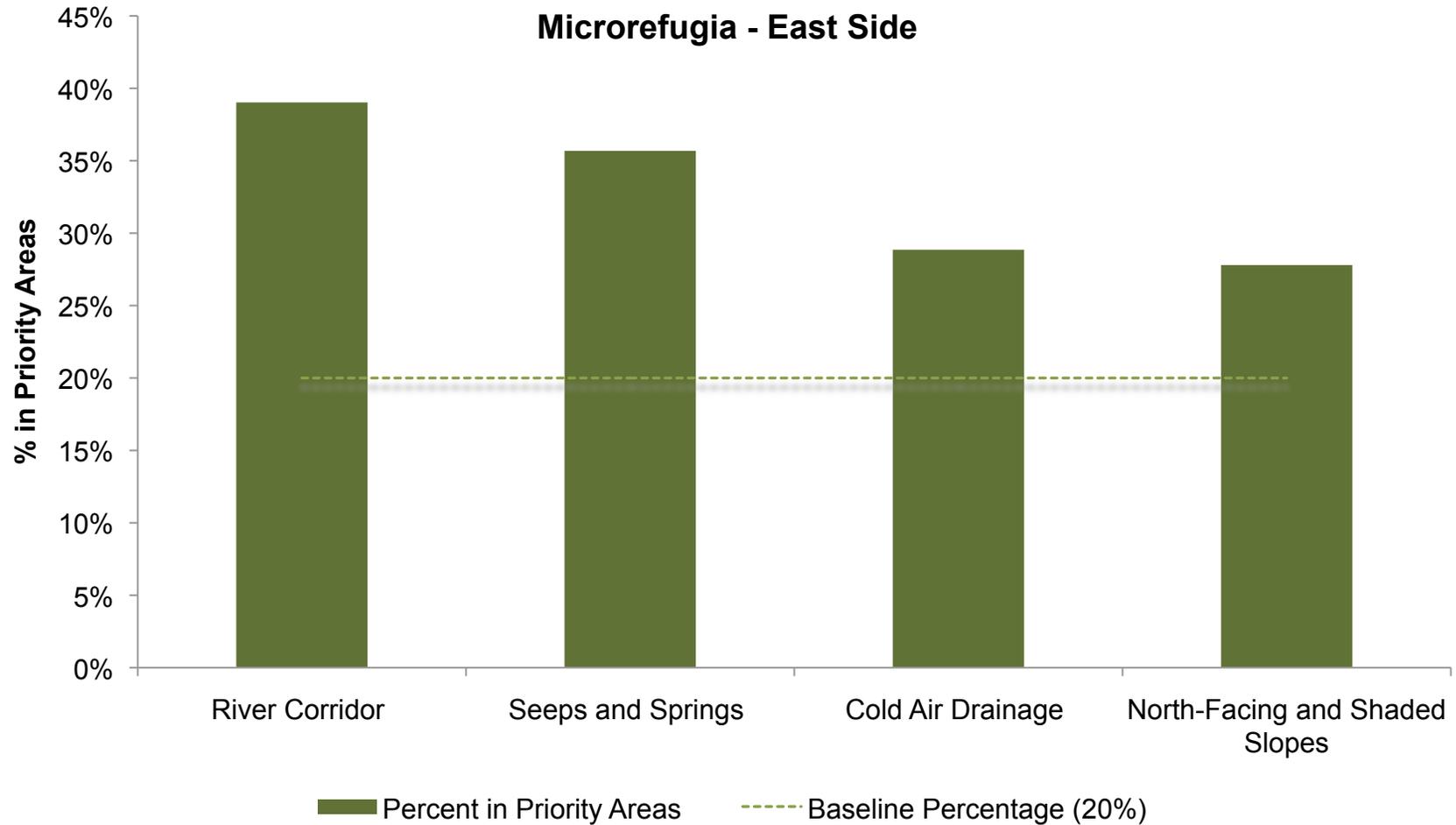


Figure 2-9. Current representation of microrefugia within NSP priority areas west of the Sierra Nevada crest.

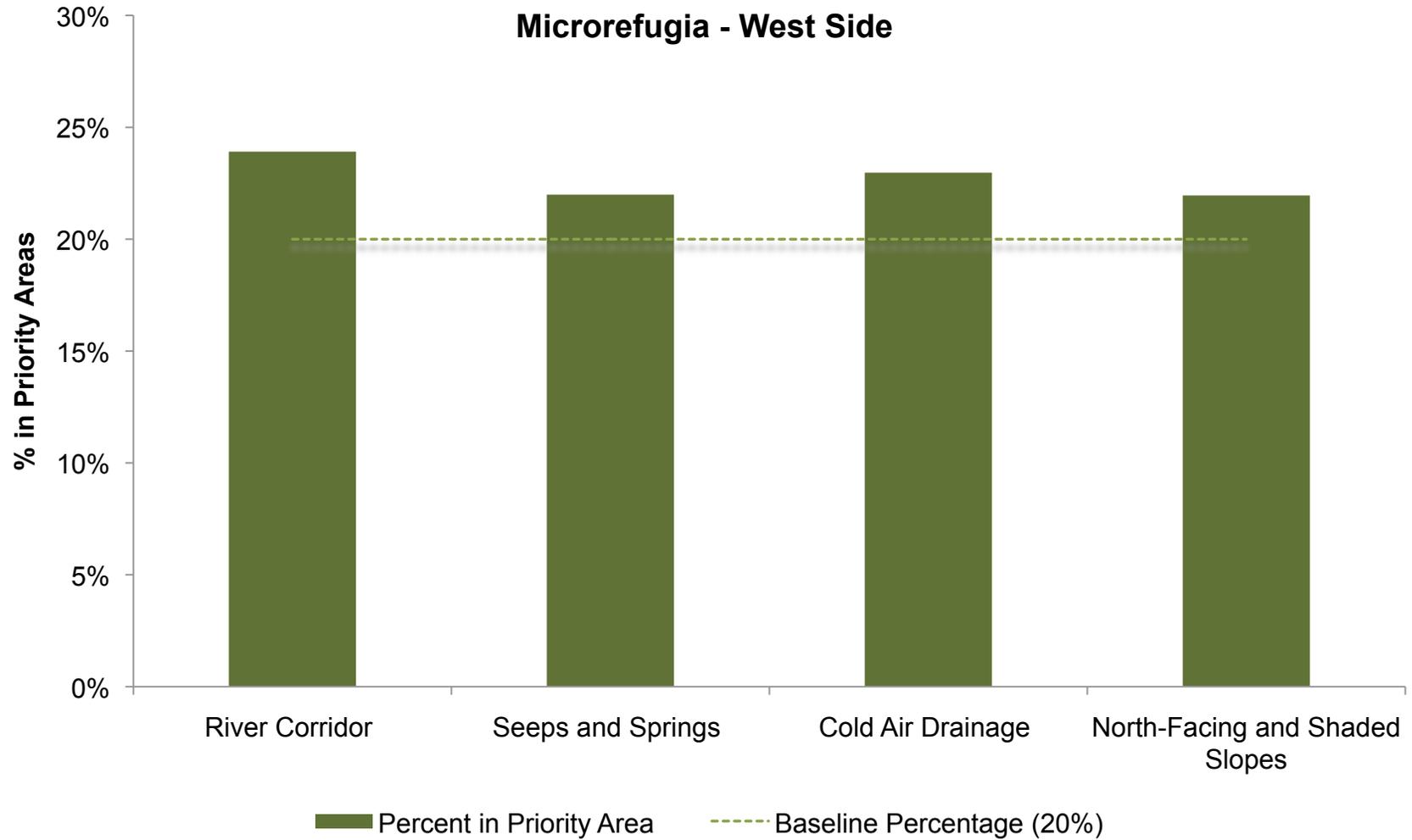


Table 2-4. Density and Diversity of Microrefugia within NSP Priority Areas	Priority area name	Percent of the microrefugia for a given side in each priority area					Index normalized by area	Feature rank
		Cold air drainage (%)	North-facing and shaded slope (%)	Seeps and springs (%)	River corridor (%)	Sum (%)		
East	Upper East Fork Carson River	6	6	18	7	37	7.8	1
East	Genessee Valley	2	4	0	2	8	6.4	2
East	Indian Valley (rank 2)	0	1	0	1	2	6.1	3
East	Indian Valley (rank 3)	0	1	0	1	3	5.9	4
West	Middle American and Rubicon Waters	5	8	8	7	28	4.8	5
West	Yuba River Watershed Mature Forest	5	6	3	5	19	4.5	6
East	Last Chance	1	0	1	0	3	4.4	7
East	Sierra Valley	4	5	11	12	33	4.3	8
East	Truckee Donner Area	6	4	2	7	18	4.1	9
East	Upper Little Truckee River	2	1	1	3	6	3.8	10
West	Middle Yuba River	1	1	0	1	4	3.7	11
East	Last Chance Creek	1	1	0	1	3	3.7	12
West	Humbug Valley	2	1	1	2	5	3.5	13
West	Sierra Buttes	1	1	1	1	3	3.4	14
East	Red Clover Valley	2	2	1	1	6	3.4	15
East	Mountain Meadows (rank 3)	4	4	1	3	12	3.2	16
West	Sierra Crest	6	3	6	5	19	3.2	17
West	Upper American River Watershed	4	3	3	3	12	3.1	18
East	Mountain Meadows (rank 2)	0	0	0	0	1	1.9	19

2.2.2.3 Representation & Interpretation of Forecasted BpS Refugia

BpS refugia provide an estimate of the relative resilience of the BpS habitat type to projected climate change. Refugia may also indicate where current conservation action is likely to protect a given BpS into the foreseeable future. To assess the performance of our BpS forecasts, we tested how well each BpS forecast accurately recovered known BpS distributions today (Figures 2.10, 2.11). High performance implied our forecasts provide future projections of habitat distributions for most of the range where habitats actually occur today. Forecasts varied significantly in terms of recovering current BpS extents, with most (n=11 of 15) providing future projections for over half of each known BpS distribution. Two forecasts showed high levels of uncertainty (e.g., < 80% model consensus across 11 futures, or no forecast at all) thus they were excluded from consideration for evaluation of conservation priorities (i.e., Pinyon-Juniper Woodlands, Montane Chaparral). Similarly, two forecasts for BpS types representative of foothill (i.e., Blue Oak–Foothill Pine) and Great Basin communities (i.e., Big Sagebrush Shrublands) were excluded from evaluations of our priorities because they are considered peripheral systems for the NSP.

Forecasts of BpS refugia often identified surprising similarities in the proportions of climate refugia versus climate stress east and west of the Sierra Nevada crest, despite stark environmental differences between the areas. Potential climate refugia dominated the current extent for five BpS forecasts (Mixed Conifer–Mesic, Yellow Pine–East Side, Ponderosa Pine–Mixed Conifer, Subalpine Woodland, Lodgepole Pine–Dry), whereas potential climate stress dominated four BpS forecasts (Red Fir–White Fir, Lodgepole Pine–Wet, Aspen Woodland, Aspen–Mixed Conifer).

Existing NSP priority areas capture $\geq 20\%$ of projected refugia for most BpS types (Figures 2-12, 2-13) in the East (n = 12 of 15) and West (n = 7 of 15). BpS types with under-represented climate refugia forecasts in current NSP priority areas (< 20% available; Figures 2-14 – 2-17) include what appear to be a mix of patchy vulnerable systems (e.g., Lodgepole Pine–Wet, Lodgepole Pine–Dry, Aspen Woodland, Aspen–Mixed Conifer) and abundant systems in the East (Yellow Pine – East Side) and West stratification units (Ponderosa Pine – Mixed Conifer).

Some priority areas capture a greater diversity and density of projected BpS refugia than others (Table 2-5). The Upper East Fork Carson River priority area captures the most refugia for the most BpS, even after normalizing by area. Genessee Valley, Upper Little Truckee River and Sierra Crest priority areas follow as the most significant areas for BpS refugia. Mountain Meadows (rank 2) contains almost no projected refugia for the species studied.

Figure 2-10. Climate Forecasts for Biophysical Settings (BpS) East of the Sierra Nevada Crest.

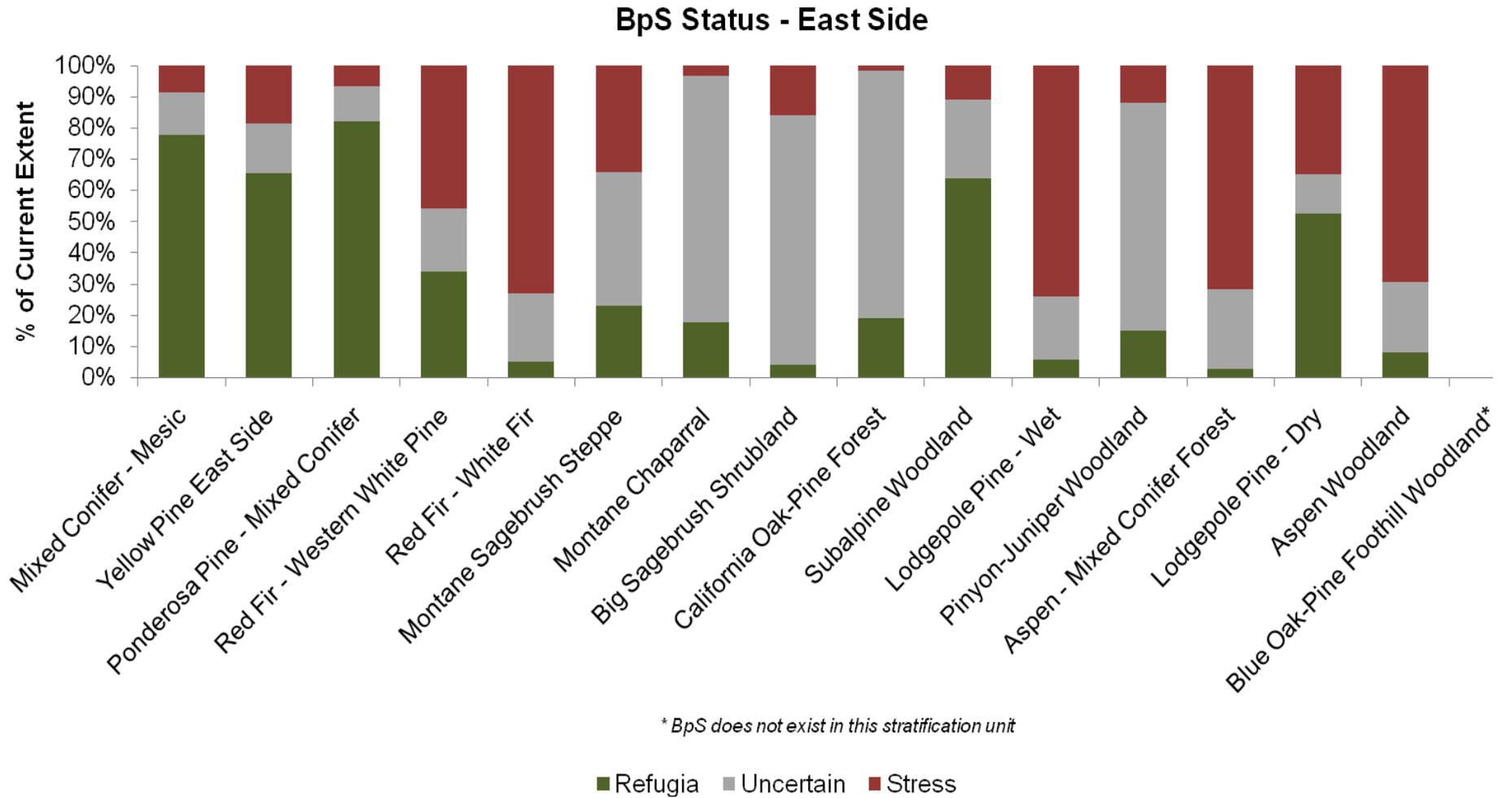


Figure 2-11. Climate forecasts for biophysical settings (BpS) west of the Sierra Nevada crest.

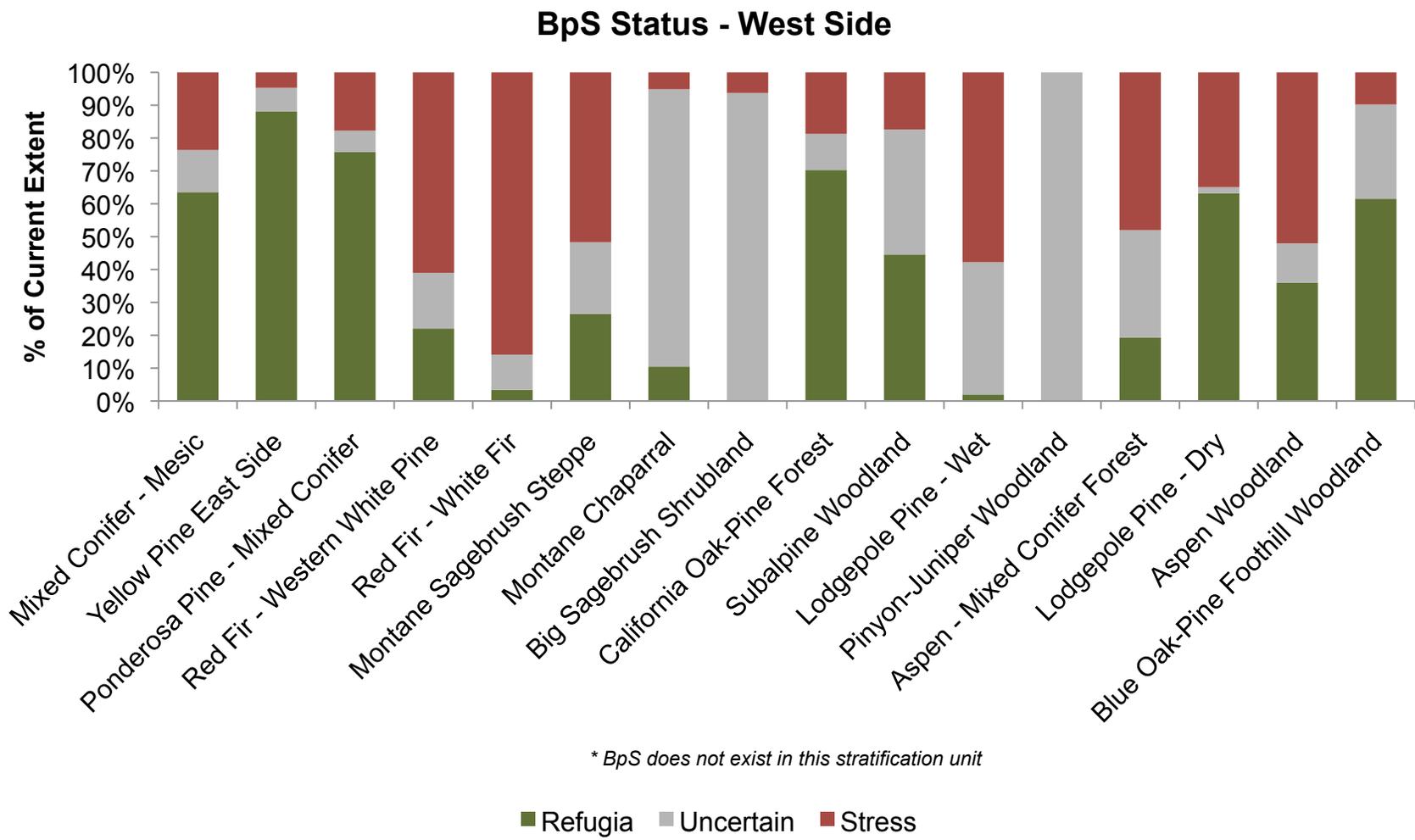


Figure 2-12. Current representation of potential climate refugia for biophysical setting (BpS) types within NSP priority areas east of the Sierra Nevada crest.

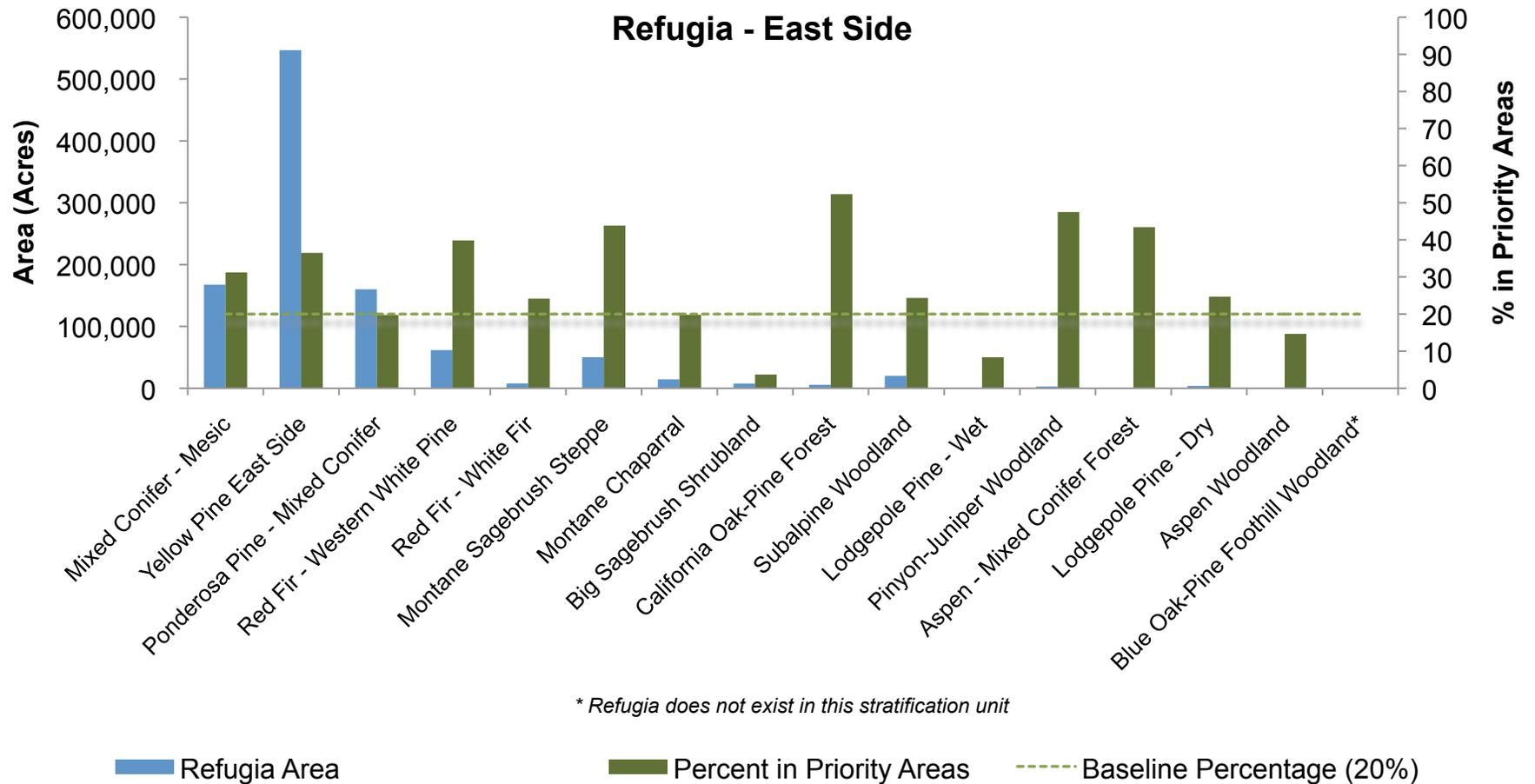


Figure 2-13. Current representation of potential climate refugia for biophysical setting (BpS) types within NSP priority areas west of the Sierra Nevada crest.

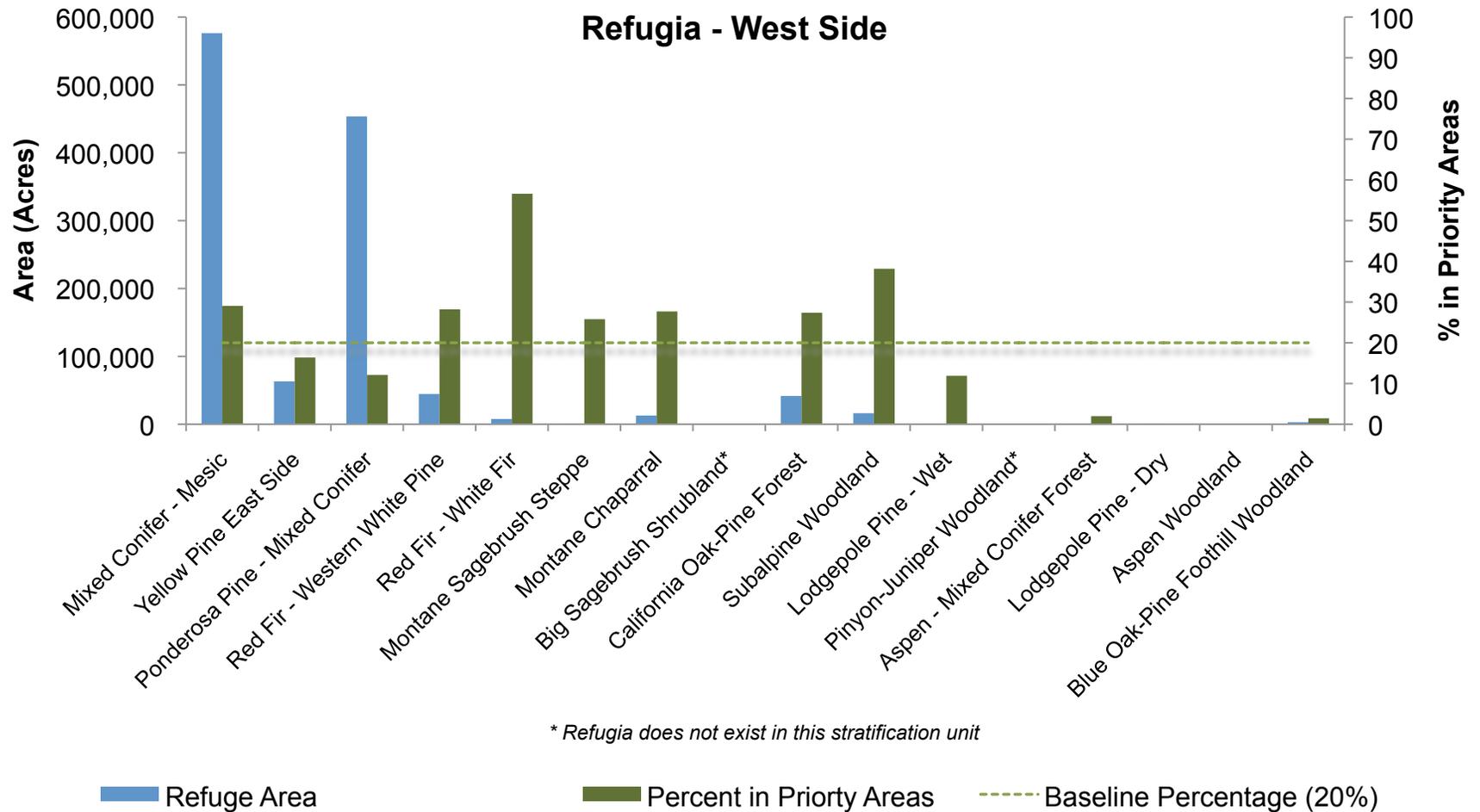


Figure 2-14. Map of potential climate refugia for both Aspen Woodlands and Aspen–Mixed Conifer forests, which are currently under-represented biophysical setting (BpS) within NSP priority areas.

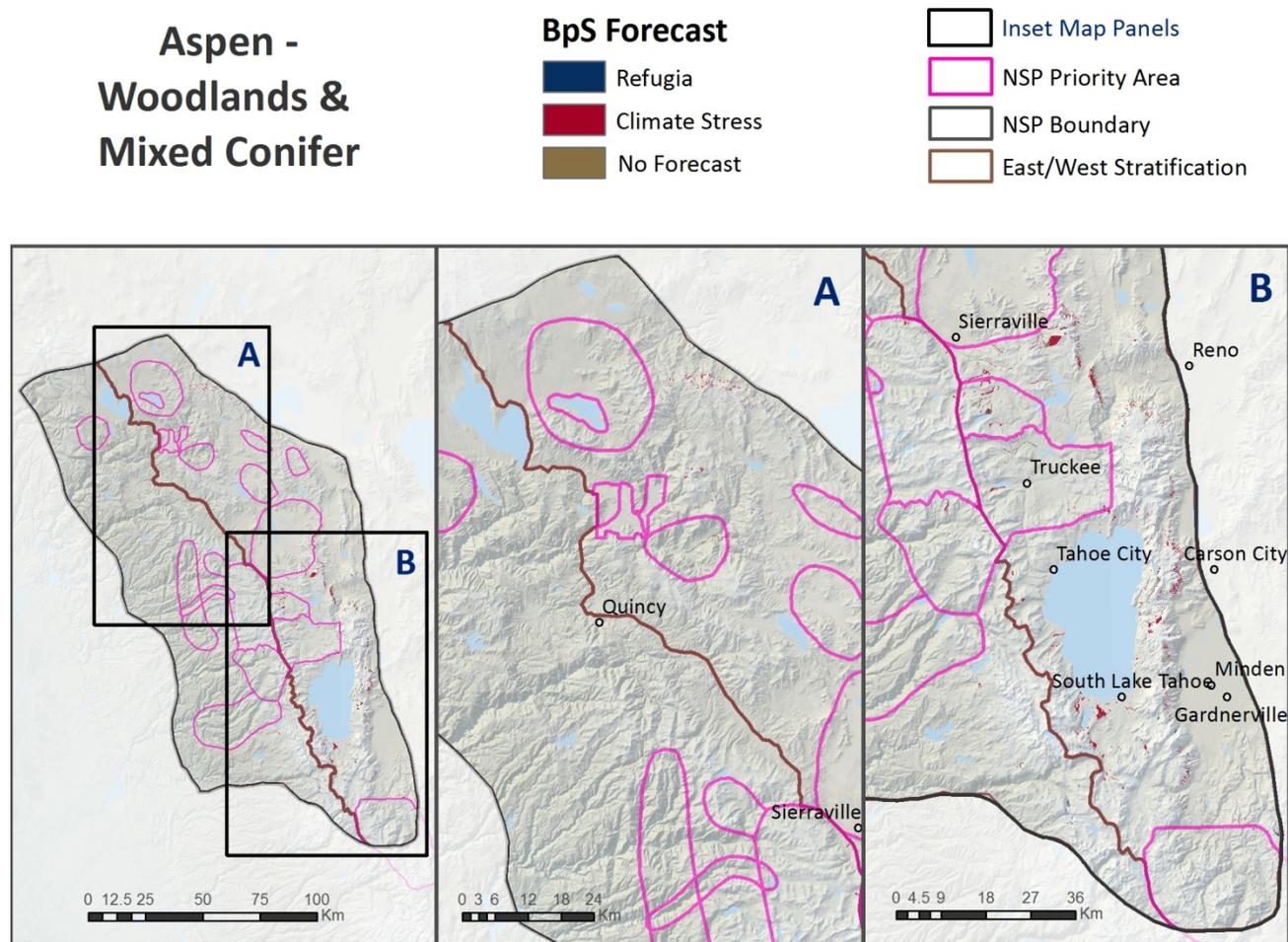


Figure 2-15. Map of potential climate refugia for both Wet and Dry Lodgepole Pine forests, which are currently under-represented biophysical setting (BpS) within NSP priority areas.

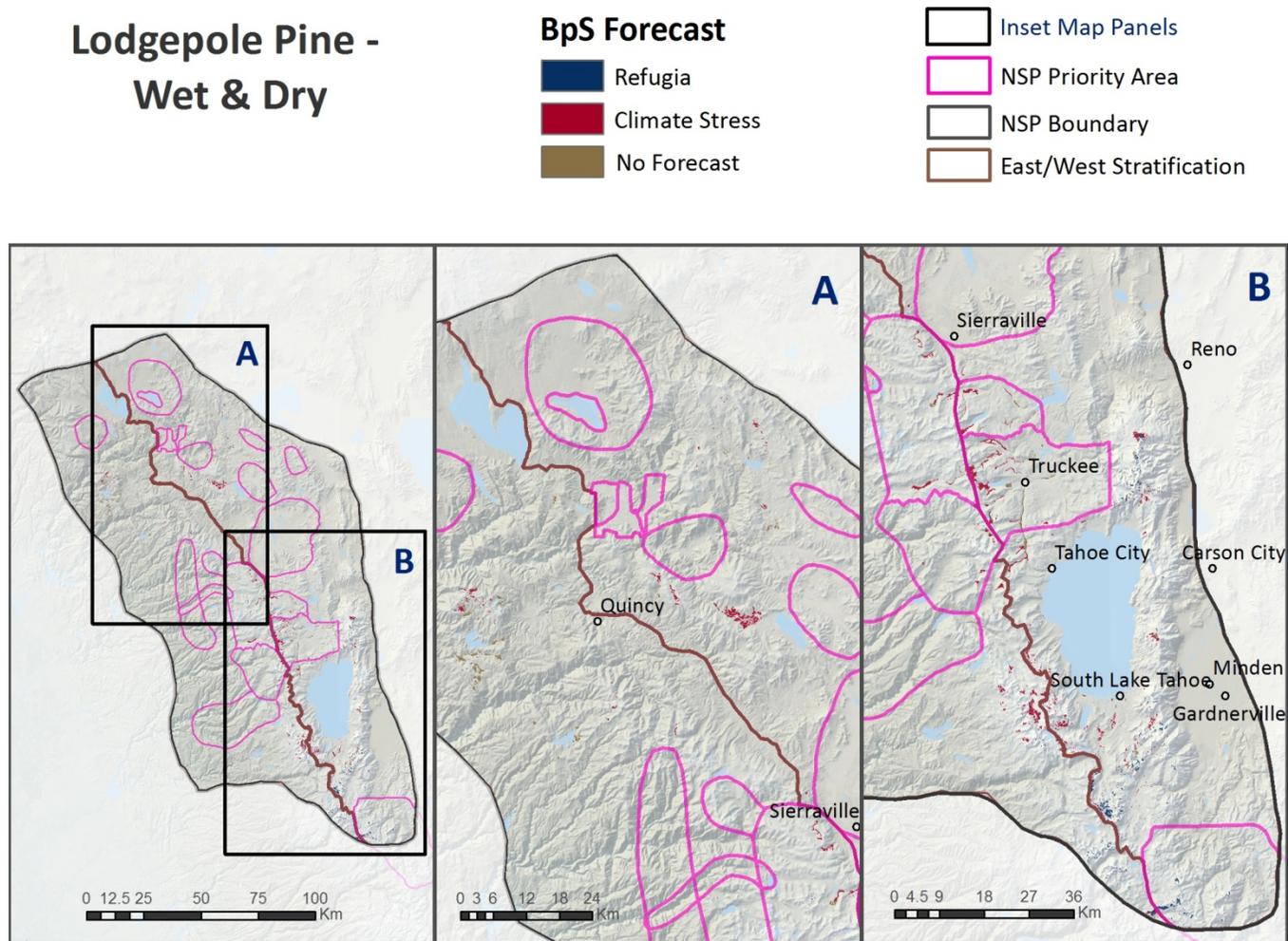


Figure 2-16. Map of potential climate refugia for Ponderosa Pine–Mixed Conifer, which is currently under-represented biophysical setting (BpS) within NSP priority areas.

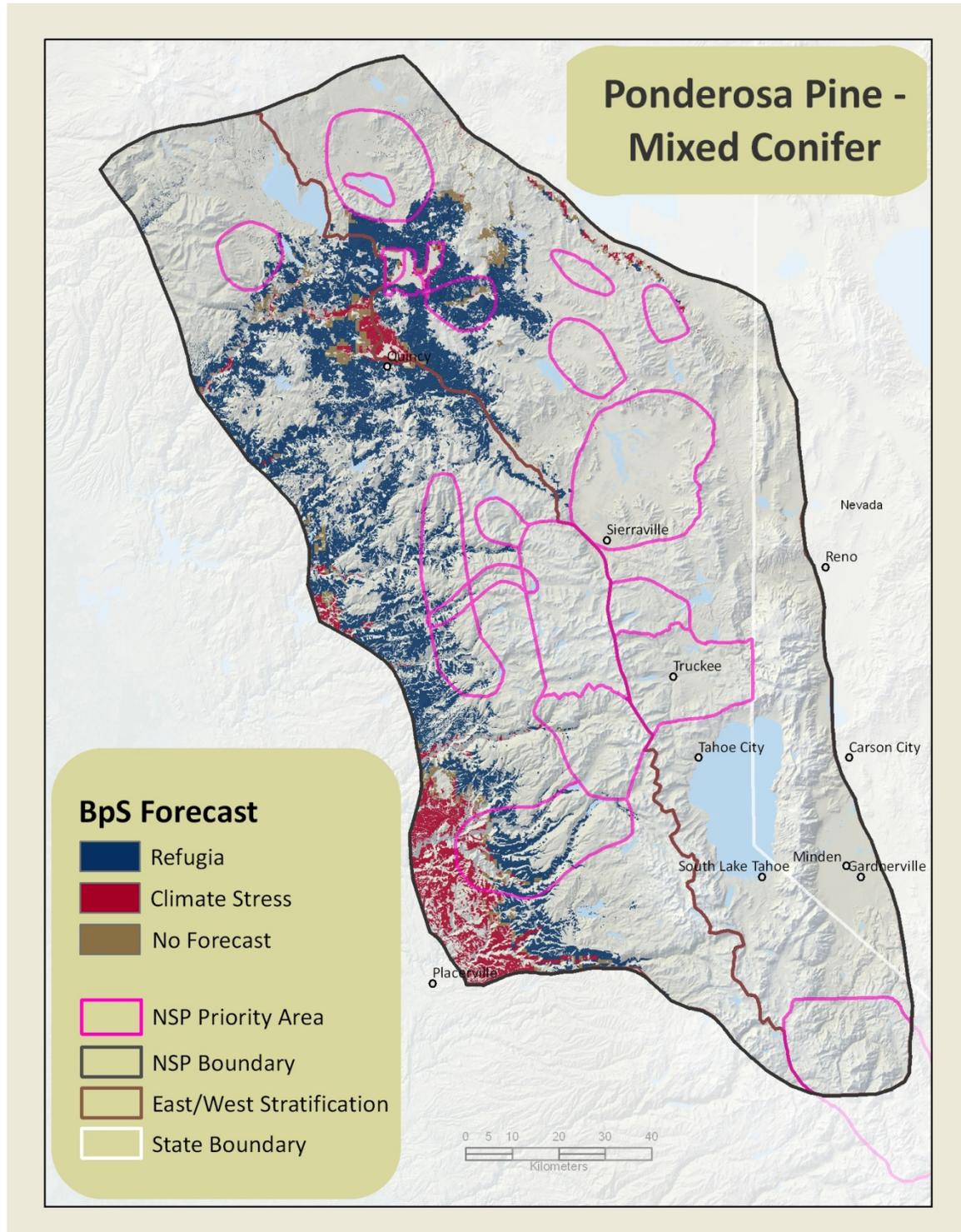


Figure 2-17. Map of potential climate refugia for Yellow Pine–East Side, which is currently under-represented biophysical setting (BpS) within NSP priority areas.

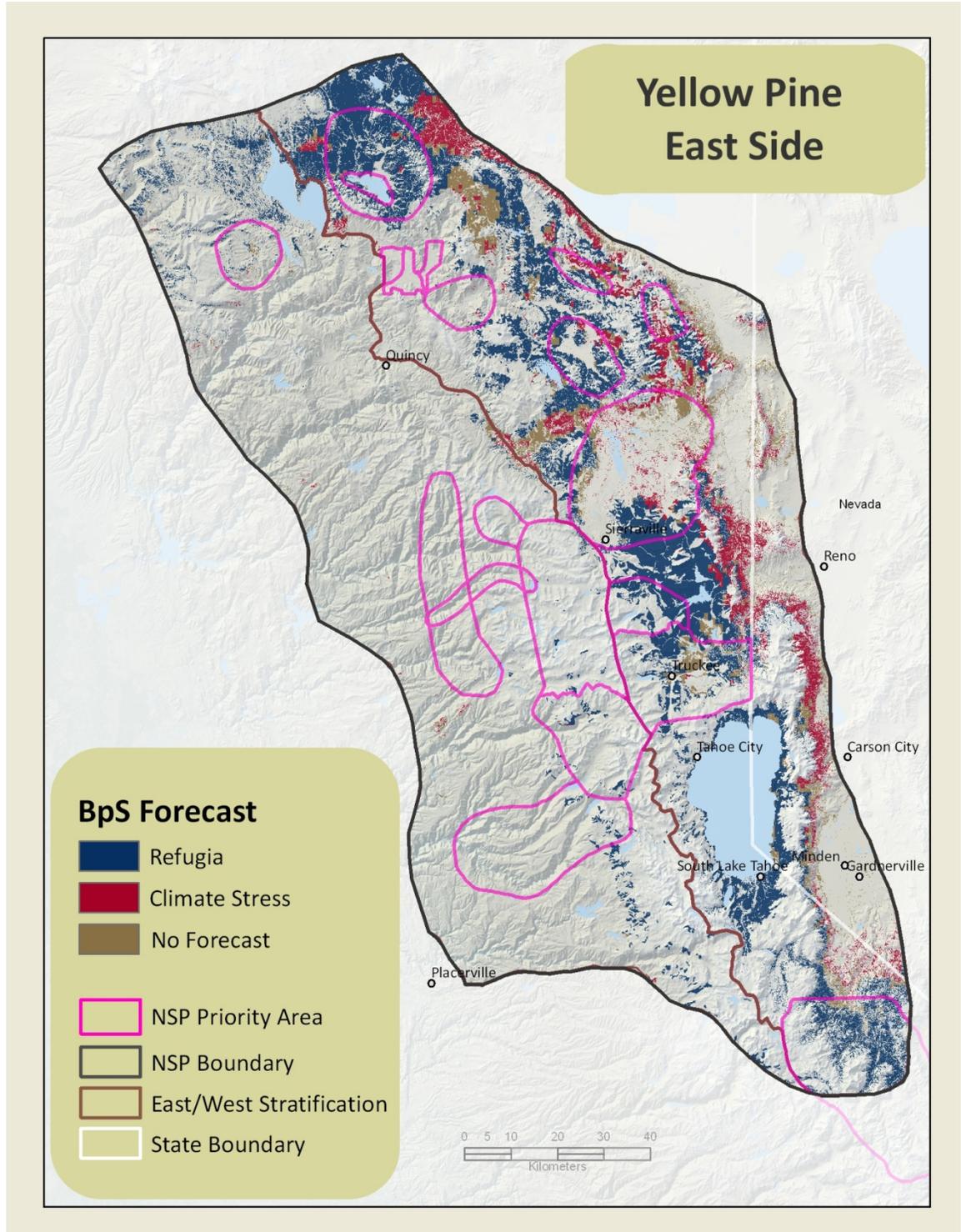


Table 2-5. Density and Diversity of BpS refugia within NSP priority areas.

Zone	Priority area name	Percent (%) of the BpS refugia for a given side in each priority area																Index normalized by area	Feature Rank	
		Mixed Conifer - Mesic	Yellow Pine East Side	Ponderosa Pine - Mixed Conifer	Red Fir - Western White Pine	Red Fir - White Fir	Montane Sagebrush Steppe	Montane Chaparral	Big Sagebrush Shrubland	California Oak-Pine Forest	Subalpine Woodland	Lodgepole Pine - Wet	Pinyon-Juniper Woodland	Aspen - Mixed Conifer Forest	Lodgepole Pine - Dry	Aspen Woodland	Blue Oak-Pine Foothill Woodland			Summed %s
East	Upper East Fork Carson River	2	7	0	40	24	7	0	3	0	16	3	47	4	25	15	n/a	192	40	1
East	Genessee Valley	1	0	13	0	0	0	2	0	25	0	0	0	0	0	0	n/a	41	34	2
East	Upper Little Truckee River	5	3	0	0	0	1	0	0	0	2	0	0	40	0	0	n/a	50	32	3
West	Sierra Crest	2	4	0	26	46	21	4	n/a	0	13	12	n/a	2	0	0	0	130	21	4
East	Indian Valley (rank 3)	0	0	2	0	0	0	0	0	7	0	0	0	0	0	0	n/a	9	18	5
West	Upper American River Watershed	6	5	0	1	6	5	3	n/a	2	25	0	n/a	0	0	0	0	53	13	6
East	Last Chance	1	1	0	0	0	0	4	0	0	0	0	0	0	0	0	n/a	6	10	7
East	Truckee Donner Area	1 0	5	0	0	0	14	0	0	0	7	6	0	0	0	0	n/a	43	10	8
East	Red Clover Valley	2	3	0	0	0	4	7	0	0	0	0	0	0	0	0	n/a	16	9	9
West	Sierra Buttes	2	0	0	0	4	0	1	n/a	0	0	0	n/a	0	0	0	0	8	9	10
West	Middle Yuba River	2	0	0	1	1	0	2	n/a	2	0	0	n/a	0	0	0	0	9	9	11
West	Yuba River Watershed Mature Forest	8	0	4	0	0	0	12	n/a	11	0	0	n/a	0	0	0	0	36	8	12
East	Indian Valley (rank 2)	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	n/a	3	7	13
East	Sierra Valley	3	5	0	0	0	13	6	0	20	0	0	0	0	0	0	n/a	48	6	14
West	Middle American & Rubicon Waters	6	4	7	0	0	0	5	n/a	11	0	0	n/a	0	0	0	1	35	6	15
East	Mountain Meadows (rank 3)	8	11	2	0	0	0	0	0	0	0	0	0	0	0	0	n/a	21	6	16
East	Last Chance Creek	0	1	0	0	0	3	0	0	0	0	0	0	0	0	0	n/a	4	6	17
West	Humbug Valley	3	4	0	0	0	0	0	n/a	0	0	0	n/a	0	0	0	0	7	5	18
East	Mountain Meadows (rank 2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	n/a	1	2	19

2.2.2.4 Ranking of Priority Areas for Adaptation

After ranking the priority areas for each of the three categories of adaptation factors (BpS richness, climatic microrefugia, BpS refugia), we combined the ranks into one summary table (Table 2-6). After adding the ranks, the priority areas with the lowest summary ranks contain the highest density and diversity of climate change adaptation factors. Based on this analysis, the Upper East Fork Carson River is clearly the best suited for climate change adaptation because it ranks highest for all three of the climate change adaptation factors we analyzed. Genessee Valley ranks well for microrefugia and BpS refugia, and the Upper Little Truckee River ranks well for BpS refugia and richness. The Mountain Meadows (rank 2) priority area is primarily a reservoir so it is not surprising that it does not rank high in this analysis that is heavily weighted towards terrestrial vegetation and landforms.

Table 2-6. Ranking of existing NSP areas for adaptation.

Zone	Priority Area Name	NSP Rank	BpS Richness Rank	Micro-refugia Rank	BpS Refugia Rank	Summary
East	Upper East Fork Carson River	3	1	1	1	3
East	Genessee Valley	1	9	2	2	13
East	Upper Little Truckee River	1	5	10	3	18
East	Truckee Donner Area	1	2	9	8	19
West	Sierra Crest	1	3	17	4	24
East	Indian Valley (rank 3)	3	18	4	5	27
West	Upper American River Watershed	1	3	18	6	27
West	Middle American and Rubicon Waters	2	8	5	15	28
East	Sierra Valley	1	7	8	14	29
West	Yuba River Watershed Mature Forest	3	13	6	12	31
East	Indian Valley (rank 2)	2	16	3	13	32
East	Last Chance	2	19	7	7	33
East	Red Clover Valley	1	9	15	9	33
West	Sierra Buttes	1	9	14	10	33
West	Middle Yuba River	1	13	11	11	35
East	Mountain Meadows (rank 3)	3	5	16	16	37
West	Humbug Valley	2	12	13	18	43
East	Last Chance Creek	1	15	12	17	44
East	Mountain Meadows (rank 2)	2	16	19	19	54

3 Strategy Development for At-Risk Major Habitat Types

3.1 Climate Adaptation Planning Methods

The goal of this section is to assess the projected impact of climate change on vegetation types in the entire Northern Sierra Partnership planning area, and to use the results to identify a suite of climate change adaptation strategies for those vegetation types that are predicted to be most at-risk from climate change. In contrast to the analysis in section 2, which focused on the NSP priority areas, the analysis in section 3 addresses all lands within the NSP boundary.

This section undertakes novel and experimental modifications to an existing public land management tool, the Vegetation Dynamics Development Tool (VDDT), in an attempt to address climate change. We present the results of a set of model runs based on a series of assumptions. We view the analytical approach as interesting and promising, but the results presented here should not be considered conclusive. Different model runs, utilizing different (and in some cases equally plausible) assumptions, would produce different conclusions. We believe there are fruitful opportunities for adjusting the basic model presented here, utilizing different assumptions and values, to address a whole host of specific questions regarding the impacts of climate change on vegetation on the northern Sierra Nevada and the steps that might be taken to address these changes.

3.1.1 Forecasting Risk to Ecosystems

A primary objective of our approach was to determine which major habitat types are at greatest “risk” due to the anticipated effects of climate change. Computerized state-and-transition models were used to assess future risk to major habitat types, as defined in terms of three metrics: (1) predicted departure from the natural range of variability (e.g., from moderate to high departure); (2) predicted conversion to high-risk vegetation (e.g., invasive species); and (3) predicted shifts in vegetation type (e.g., from red fir-western white pine to mixed conifer). The definition of risk that we used did not consider the total acreage of a habitat type as a factor; weighting the acreage proportionally would have produced different results, with vegetation types having larger acreage being considered to be at higher risk. Similarly, although wildfire was considered at various stages of our analysis, the risk of high-intensity wildfire causing damage to property and lives was also not elevated in importance relative to other projected changes in this analysis.

The methods previously described in this paper helped provide a foundation: climate models were used to help develop species distribution models, and in turn both of these were used to help refine the ecological models to forecast future conditions. Section 3.3 of this report describes how the ecological models were further used to test alternative management strategies to help abate the predicted impacts to at-risk systems. The following description is an overview of methods, whereas Appendix A presents the full account.

We quantitatively assessed the current condition of 25 BpS habitat types using LANDFIRE classifications (<http://gisdata.usgs.net/website/landfire/>) in the project area by measuring ecological departure for each system (Hann and Bunnell 2001; Provencher et al. 2008; Rollins 2009). *Ecological departure* is the dissimilarity between a BpS's current (or future simulated) condition and its natural range of variability (NRV). NRV reflects the distribution of vegetation classes that would be expected under naturally functioning ecological processes, as predicted by field studies, expert opinion, and computer simulations. We assessed projected future conditions – with and without projected climate change impacts – for ecological systems using the Vegetation Dynamics Development Tool software (VDDT, by ESSA Technologies, Ltd; Barrett 2001; Beukema et al. 2003) that is used for vegetation modeling and landscape conservation forecasting (Forbis et al. 2006; Provencher et al. 2007, 2008; Low et al. 2010). Based upon these results, we identified which BpS habitat types are “at risk” due to projected climate changes impacts.

Temporal multipliers are a key component to modeling climate variability and change. A temporal multiplier is a number in a yearly time series that multiplies a base disturbance rate in the VDDT models: for example, for a given year, a temporal multiplier of one implies no change in a disturbance rate, whereas a multiplier of zero is a complete suppression of the disturbance rate, and a multiplier of three triples the disturbance rate. We used time-series data of observed historical events (droughts, fires, floods, insect and disease invasions) as the basis of our temporal multipliers. Most often, temporal multipliers were converted to a unitless value by dividing each annual value from the historical time-series by the average value from the entire time-series. Temporal multipliers can further be modified to reflect a hypothesized change caused by external factors, such as climate change.

For estimating the natural range of variability (NRV), the Palmer Drought Severity Index (PDSI) was used as the basis for most temporal multipliers, including three different levels of fire severity (surface, mixed, and replacement), for three major vegetation groups (Taylor and Beatty 2005; Westerling et al. 2006; Westerling and Bryant 2008). Flow data were used to create temporal multipliers for montane riparian systems. For management models, a different set of historical data was used for temporal multipliers. The methods and data used to generate the temporal multipliers are presented in Appendix A.

The project area was stratified into two large sub-regions – Eastside and Westside – which have very different climates and differing arrays of ecological systems. All analyses were conducted for both the Eastside and Westside sub-regions.

3.1.1.1 Modifying a Vegetation Model to Reflect Climate Change

3.1.1.1.1 Hypotheses of Change

We developed a table of predicted ecological impacts resulting from climate change (hypotheses of change) for each system based upon future climate scenarios described in Appendix A. Some hypotheses were directly supported by recent publications, albeit few, whereas the remaining hypotheses were inferred. Hypotheses of change, the type or magnitude of the disturbances causing change in the models, and temporal multipliers as described below in “Future Annual Variability” were reviewed in expert workshops or by selected natural resources experts:

Directly supported hypotheses:

- More frequent, larger fires (Brown et al. 2004; Westerling and Bryant 2008; Westerling, *in press*)
- Higher tree mortality during longer growing season droughts (Pennisi 2009)
- Longer period of low flows (Dettinger et al. 2004; Maurer 2007; Stronstrom and Harrill 2006)
- Longer period of groundwater recharge during colder months (more effective recharge) (Stronstrom and Harrill 2006; personal communication, Dr. Rick Niswonger, USGS Carson City, 2008)
- Increased dispersal of non-native species (Bradley 2009; Brown et al. 2004; Smith et al. 2000)

Inferred hypotheses:

- Greater conifer and deciduous tree species recruitment and growth in meadows/wetlands/riparian due to drought and CO₂ fertilization (Brown et al. 2004)
- Impaired recruitment of willow and cottonwood due to modified hydrology (Maurer 2007)
- Faster growth of fast-growing native tree species (Brown et al. 2004; personal communication, Dr. Hugh Safford, US Forest Service, University of California at Davis, 2008)
- Increased recruitment of high-elevation trees (personal communication, Dr. Hugh Safford, US Forest Service, University of California at Davis, 2008)
- Increased dispersal of pinyon and juniper in shrublands (Tausch and Nowak 1999).

3.1.1.1.2 Future Annual Variability

In order to model the impacts of climate change on the BpS, we incorporated the hypotheses of change into our ecological models by making several changes to the input data. We modified several temporal multipliers (see Appendix A) from the east and west sides using predictions from the Parallel Climate Model (PCM; Dettinger et al. 2004) with the A1Fi business-as-usual emissions scenario. These modifications to the ecological models require a full time series of future climate projections (i.e., every year from 2000-2050). While data from the other 11 GCMs listed in Table 2.1 were available for one 20-year period (2046-2065) for this area, a downscaled time-series of data for this area was not readily available. Thus, we focused only on the results of the PCM GCM for this portion of the analysis.

We modified the fire temporal multiplier to simulate future forest fires under a hotter climate, with increasing greenhouse gases, but same total precipitation (Figure 3-1; IPCC 2007; Dettinger et al. 2004). To make this change, we multiplied the fire temporal multipliers for each of the five major vegetation groups, for the three different fire severities, by the predicted temperature temporal multiplier (yearly temperature predicted by PCM divided by the temperature in the first year of the time series; Figure 3-1). Under this assumption higher temperature caused more fire activity in a linear manner, which is the simplest assumption.²

We similarly modified the other temporal multipliers relating to drought, invasion rates, soil moisture, and flows. Drought was modified using the PSDI (Appendix A) and predicted temperature increases from Dettinger et al. (2004; Figure 2-6). Flow temporal multipliers were generated with historic USGS gage data from the Truckee River and Feather River. The peak flow temporal multiplier was modified for climate change under the assumptions that peak flows and their variability would increase with time due to more frequent rain-on-snow events and early snow melt (Dettinger et al. 2004; Maurer 2007). With climate change, peak flow is predicted to occur increasingly earlier (Maurer 2007), which would be before flowering and seed deposition of cottonwood and willow. Although not documented in the literature, we hypothesized that earlier onset of future peak flow will have a depressing effect on cottonwood and willow recruitment, but higher and more variable future peak flows will partly compensate for loss of recruitment success. Early snow melt would also cause greater late summer mortality of willow and cottonwood seedlings by desiccation, as captured by the seedling mortality temporal multiplier (personal communication, Dr. Rick Niswonger, USGS Carson City, 2008). Finally, we hypothesized that carbon from enhanced atmospheric green house gases (IPCC 2007; Figure 3-1) would fertilize exotic forb species growth during year of greater

² Westerling and Bryant (2008) showed nonlinearities between area burned and maximum temperature; however, their predictions under the A2 emissions scenario showed a nearly linear relationship between percent change in number of voxels (i.e., unit of latitude × longitude × month) burned with fires >200 ha and future years of simulation.

soil moisture (Bradley 2009; Smith et al. 2000), which we equated with annual flows. Appendix A describes more fully the modifications to the temporal multipliers used to simulate future conditions under climate change.

3.1.1.1.3 Vegetation Shifts

To simulate potential future shifts in BpS, we first determined the *rate* of projected shift, and then determined the *type* of projected vegetation shift.

As described in Section 2.1.4.2, we used future “climate envelope” projections for major tree and shrub species to show predicted *rates* of stress over the next 80 years for the associated biophysical settings. The rate of stress in the VDDT models was the proportion of a BpS experiencing stress as calculated in Section 2.4 divided by the number of years projected (i.e., 80 years). Projected stress areas for a given species were assumed to equate with likely conversion because the species would not reproduce under the new climatic conditions. It was realized that a BpS might persist beyond the 80 years of predicted stress because adult trees can survive although their offspring fail to establish. To minimize this problem, BpS conversion in the models only occurred when a stand-replacing disturbance killed adults; in other words, a BpS could persist for longer than predicted if it did not experience significant stand replacing events. This adjustment led to another problem: some subalpine and aspen BpSs that were predicted to experience very high levels of stress did not experience vegetation shifts rapid enough to “keep up” with predicted stress over 80 years because the natural disturbance rates are too slow (for example, a long mean fire return interval). In these cases, 100% of all stand-replacing events caused a vegetation shift, although conversion was still not “fast enough.”

To forecast the *type* of biophysical settings that would replace a stressed one, we used Dr. Jim Thorne’s shared data (<http://ice.ucdavis.edu/project/wieslander>) on actual vegetation conversions based on the analysis of Wieslander Vegetation Type data for the Sierra Nevada (<http://vtm.berkeley.edu>). One critical assumption made here was that vegetation transitions from the last 80 years were the best guess to future transitions for our VDDT simulations with climate change effects. Another critical assumption is that historical vegetation transitions relate to climatic changes, as opposed to alternative drivers (e.g., human activity, fire, succession, disease, error). Using recently interpreted aerial and satellite imagery and USFS plot data and maps, Thorne and others determined the California Wildlife Habitat Relationship (WHR) vegetation types currently at the location of the Wieslander plots (Thorne et al. 2008).

Thorne’s matrix of “before and after” frequency transitions among WHR types over a period of approximately 80 years revealed often different pathways of vegetation change for the same starting vegetation type. We crosswalked the WHR types to the closest BpSs using characteristic species and type descriptions (Appendix A). We eliminated from the “after” types those that represented the outcome of fire exclusion pathways that are contained in the VDDT management models. For example, mixed conifer in 2009

that replaced ponderosa pine from 1920 was considered a false change because fire exclusion or logging alone could explain the results and our models already account for these false changes. As a general rule, a transition was termed “true” if the new vegetation type had a mean fire return interval that was comparable or shorter than the original Wieslander type’s mean fire return interval. An example of a “true” transition would be the ponderosa pine type being replaced by the California mixed evergreen type. The data for true conversion when more than one transition pathways were documented were used to split proportionally the rate of transition (previous paragraph) using ratios calculated from the Thorne data. Further justification and explanations are found in Appendix A.

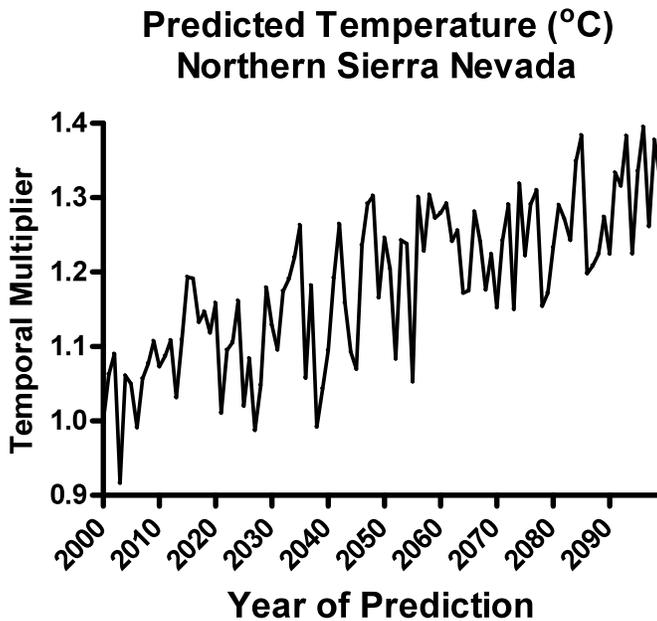
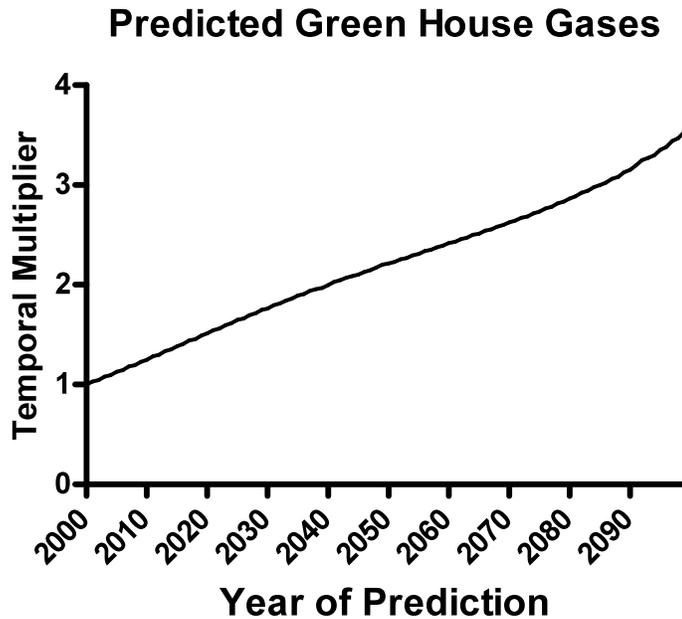
3.1.1.2 Simulating Future Conditions – With and Without Climate Change

Using VDDT models, we simulated the likely future condition of each ecological system after 20, 50 and 80 years, assuming minimum management (e.g., no treatment of exotic forbs, no prescribed fire, and no active management of livestock). Potential sources of future impairment were explicitly modeled, and included the following: non-native species (cheatgrass and exotic forbs) invasion, tree encroachment, altered fire return intervals, entrenchment of and water diversion from creeks and wet meadows, and excessive herbivory by livestock.

For each simulation, the models were run with five replicates to introduce natural and future alternative variability, with each replicate incorporating a different set of temporal multipliers for each of the different disturbance parameters in the VDDT models. We measured three outcomes using the mean of the five replicates: Ecological Departure; Percentage of High-Risk Vegetation Classes; and Percentage of Vegetation Shifts.

These simulations were conducted under two scenarios: (1) with no future climate change effects incorporated in the models; and, (2) with the above-described climate change effects incorporated as uniquely expressed by temporal multipliers and vegetation conversion pathways. The *with* versus *without* scenarios allowed us to project the marginal effects that are expected as a result of climate change.

Figure 3-1. Temporal multiplier of temperature for the Northern Sierra Nevada (based on Dettinger et al. 2004) and global green house gases (based on IPCC 2007) under the “business-as-usual” (A1Fi) climate change scenario. Temperature raw data obtained from Dr. M. Dettinger, USGS, 2009 based on the PCM simulations. The green house gases and temperature temporal multipliers were each calculated by dividing each yearly value by the value of the first year of the time series.



3.1.2 Testing Strategies for At-Risk Ecosystems

The methods used for strategy forecasting have been deployed previously by TNC with public land management agencies for landscape-scale conservation planning in Nevada, Utah and California, including projects with the U.S. Forest Service (USFS), Bureau of Land Management (BLM) and National Park Service (NPS). We used VDDT models to test alternative management strategies for the subset of ecosystems which were forecast to be most at-risk due to projected climate change impacts, in terms of (1) departure from NRV; (2) increase in high-risk vegetation classes (high-risk vegetation classes are unrelated to climate change risk; Low et al. 2010); and/or, (3) vegetation shifts. Strategies were sought that would meaningfully reduce the climate change risk and increase ecosystem resilience (described below).

Working with USFS and members of the Partnership and drawing upon previous strategy simulations developed with USFS, BLM and USGS natural resources management staff, a suite of potential management strategies (below) was developed for each of the at-risk ecological systems, as well as the estimated costs of implementing each strategy. The projected ecological effects of each strategy were incorporated into the VDDT models as disturbances with average implementation rates (e.g., prescribed fire is the disturbance applied at about 5,000 acres per year). The models also included a “failure rate” expressed as a proportion for some management strategies to reflect that some management actions only partially succeed at restoring a vegetation class. Failure rates were drawn from our experience with past agency projects (Provencher et al. 2007, 2009; Low et al. 2008) and discussion with USFS Region 5 staff. The array of management strategies included the following:

Forest and woodland strategies

- prescribed fire
- mechanical thinning

Riparian and wet meadow strategies

- weed inventory
- spot application of herbicides
- restoration of entrenched areas
- restoration of shrub-forb encroached areas
- grazing management

Various combinations of management strategies were explored for each targeted ecosystem, using VDDT computer simulations to test their effectiveness and adjust the scale of application. A management strategy is an action applied to specific vegetation classes of a BpS, such as prescribed fire used in closed late-succession aspen mixed-conifer forest, whereas a combination of strategies represents all such actions applied to a single BpS. Since VDDT software does not have an optimization mechanism, we tested different combinations of alternative management strategies (e.g., prescribed fire and thinning versus just prescribed fire) and levels of treatment (yearly average area of application per action). Through this trial-and-error process of changing types of actions

and yearly application rates, we created a set of strategies designed to reduce ecological departure and high-risk vegetation classes (including reducing the area of vegetation conversions).

Management strategies were modeled over 50 years using a two-step approach, with 20 year model run outputs calculated as the first step. The outputs were then used as the starting conditions followed by 30 year model runs that incorporated climate change impacts. This approach was used for two reasons. First, climate change effects are expected to accelerate over the 50 year time horizon, with the most dramatic impacts occurring later rather than sooner. Model runs from previous projects (Provencher et al. 2009) and model calibration for this project showed that the signal of climate change effects started being detected from the large variability introduced by temporal multipliers at about 40 years. Secondly, previous management model runs for Great Basin National Park often showed dramatic improvements as a result of front-loading management treatments in early years. The two-step approach – 20 years, then 30 years with climate effects kicking in – allowed us to more accurately capture the likely effects of early management actions. These outcomes are compared to the more dramatic “minimum management” scenario in which climate change impacts are modeled to begin immediately in year one.

Estimated costs for each management strategy were based upon estimates provided by public agency and land trust partners. In actual on-the-ground applications, these costs will vary greatly depending upon local circumstances. For purposes of this coarse-scale benefit-cost strategy assessment we are using a mid-point or a typical cost for a given treatment.

Strategies were tested using two broad scenarios: (1) maximum management, which sought to achieve the best ecological outcomes regardless of cost; and, (2) streamlined management, which sought to achieve positive ecological outcomes while minimizing cost over the duration of simulations, using a return-on-investment approach (greatest combined improvement in the three metrics for the lowest cost).

3.2 Climate Adaptation Key Findings About ‘What to Do’

3.2.1 Development of Cost-Effective Adaptation Strategies

3.2.1.1 Presentation & Interpretation of Ecological Departure Forecasts

A primary objective of the Northern Sierra climate adaptation planning is to forecast the future condition of the region’s ecological systems and determine which systems may be at greater risk due to the anticipated effects of climate change. Future risk to the ecological systems was assessed using ecological models via three metrics: (1) predicted departure from the natural range of variability; (2) predicted percentage of high-risk vegetation; and, (3) predicted shifts in vegetation type. As discussed above, using different risk criteria would have produced different results. Active management will be needed to reduce these future risks for several systems under a changing climate, and will be discussed in Sections 3.2.1.1.1 and 3.2.1.1.2.

3.2.1.1.1 Current Condition: Ecological Departure

The current condition of the Northern Sierra’s ecological systems varies in terms of departure from their NRV. Of the area’s 25 ecological systems, ten are considered slightly departed from their NRV, twelve are considered moderately departed, and three are considered highly departed (Table 3-1). The actual reason for current departure – that is, the dissimilarity between the mix of vegetation classes currently present versus the mix of classes “expected” in NRV – differs for each individual ecological system. Appendix C provides a written summary description of the current condition of each system across the region. Appendix D shows for each ecological system the acreage, percentage of current vegetation classes, percentage of classes in NRV, and resulting ecological departure score – broken out by eastside and Westside. The overall Northern Sierra departure scores were calculated as a weighted average of the eastside and westside scores.

We stress that the descriptive terms “low,” “moderate,” and “high” are subjective, and that depending upon the circumstances, ecological values, and acreage involved, our conclusions regarding which deviations are considered “low,” “moderate,” or “high” might differ. In addition, the net effect of departure on ecosystem functioning and dynamics is not linearly related to the magnitude of departure. To assume that the NRV was always a preferred state for all species and ecosystem processes is likely too simplistic given the complexity of habitat use preferences and shifts in response to environmental change. Additionally, a relatively small departure in a widespread system may have greater ecological consequences than a large departure in a restricted system. The geographic extent of the ecosystem in question can provide a greater influence on landscape dynamics, including surface water flows, disturbance regimes and habitat

values, than the degree of departure. Other reviewers might consider many or all the departures that we report here to be ecologically significant. We also note that the results presented here lump together all seral stages within each vegetation class, which may obscure significant departures from NRV for particular seral stages within some ecological systems.

For example, as shown in Table 3-1, “mixed conifer mesic” is currently considered to have “low departure” from NRV. Yet, as shown in Appendix D, large tree forests within this type (class D and E) are currently significantly underrepresented compared to NRV – 28% current versus 41% NRV on the westside, and 24% current versus 41% NRV on the eastside, for a weighted average of approximately 27% current versus 41% NRV. Similarly, an examination of the NRV departure for large tree classes within other widespread forest types, such as Yellow Pine eastside, Ponderosa Pine–Mixed Conifer, and Red Fir–Western White Pine, shows that late seral stage forests are significantly underrepresented compared to NRV. This result is consistent with the scientific literature indicating that old forest habitat in the northern Sierra Nevada has been greatly depleted. However, for purposes of simplicity in this analysis, we do not weight departure from any one seral stage or class higher than any other class when calculating ecological departure for a ecological system.

3.2.1.1.2 High-Risk Vegetation Classes

A high-risk class was defined as an uncharacteristic vegetation class that met at least one of the three following criteria: (1) $\geq 5\%$ cover of invasive non-native species, (2) vegetation type conversion or (3) very expensive to restore. “Very expensive” represents a subjective judgment based on per acre costs. For purposes of this analysis, large areas requiring restoration, such as mixed conifer forests that are at high risk of stand-replacing wildfire due to past logging and fire suppression, are not considered “very expensive” to restore, even though the total costs of restoration, based on the large acreage involved, could be very large.

Similar to the grouping of ecological departure scores into three ecological condition classes, the cover of high-risk vegetation classes was stratified into four categories.

- **Low:** 0% cover of high-risk vegetation classes, no future risk posed to ecological system condition.
- **Medium:** 1-10% cover of high-risk vegetation classes, acceptable future risk posed to ecological system.
- **High:** 11-30% cover of high-risk vegetation classes, future vegetation classes have the potential to catalyze even greater degradation of a ecological system and will require significant resources to contain, let alone restore.

- **Very High:** >30% cover of high-risk vegetation classes, the system will be highly degraded, perhaps beyond the ability of managers to recover the ecological system.

The Northern Sierra's ecological systems vary in terms of the current amount of high-risk classes that they possess, but most systems currently have no or little high risk classes. Of the area's 25 systems, only two have a Very High amount of high-risk vegetation classes, one system has a High amount; six systems have a Medium amount; and sixteen systems have no high-risk classes (Table 3-2). We acknowledge that some of these results appear to be counter-intuitive, especially with respect to fire-adapted forest ecosystems in the northern Sierra. We emphasize that we define "high risk" quite conservatively and many systems for which structural characteristics and functional regimes (e.g., disturbance) have changed with past extraction and management objectives do not register as "high risk" yet represent significant management challenges currently.

Table 3-1. Percent departure of ecological systems of the Northern Sierra from their natural range of variability, grouped by elevation and/or vegetation type and their respective size. Ecological departure is color-coded: green = low departure, yellow = moderate departure, and red = high departure.

Ecological System	Acres	Current Condition
Subalpine		
Alpine Shrubland	1,600	13
Lodgepole Pine – Dry	8,900	59
Lodgepole Pine – Wet	21,800	53
Red Fir – Western White Pine	379,000	37
Red Fir – White Fir	370,600	34
Subalpine Meadow	1,300	27
Subalpine Woodland	66,100	20
Mid-Elevation Forests		
Aspen–Mixed Conifer Forest	12,100	62
California Oak–Pine Forest	63,300	50
Mixed Conifer – Mesic	1,100,200	26
Ponderosa Pine – Mixed Conifer	783,600	41
Yellow Pine	889,900	54
Low-Elevation Forests		
Blue Oak–Pine Foothill Woodland	4,700	49
California Mixed Evergreen Forest	66,300	13
Xeric Shrublands		
Montane Chaparral	187,200	5
Serpentine Woodland & Chaparral	8,100	68
Mid-Elevation Eastside Shrublands/Woodlands		
Aspen Woodland	6,400	28
Big Sagebrush Shrubland	184,400	46
Curlleaf Mountain Mahogany	12,600	48
Low Sagebrush	16,500	14
Montane Sagebrush Steppe	206,200	30
Pinyon Juniper	19,200	32
Riparian and Wet Meadows		
California Montane Riparian	58,100	36
Great Basin Riparian	27,300	71
Wet Meadow	108,400	83

Table 3-2. Current percent of high-risk vegetation classes for Northern Sierra ecological systems. Stress to ecological systems is ranked as: low (0%, dark green); medium (1-10%, light green); high (11-30%, yellow), and very high (>30%, red).

Subalpine	
Alpine Shrubland	0
Lodgepole Pine - Dry	0
Lodgepole Pine - Wet	0
Red Fir - Western White Pine	0
Red Fir - White Fir	0
Subalpine Meadow	0
Subalpine Woodland	0
Mid-Elevation Forests	
Aspen-Mixed Conifer Forest	1
California Oak-Pine Forest	0
Mixed Conifer - Mesic	0
Ponderosa Pine - Mixed Conifer	0
Yellow Pine	0
Low-Elevation Forests	
Blue Oak-Pine Foothill Woodland	0
California Mixed Evergreen Forest	0
Xeric Shrublands	
Montane Chaparral	0
Serpentine Woodland & Chaparral	0
Mid-Elevation Eastside Shrublands/Woodlands	
Aspen Woodland	0
Big Sagebrush Shrubland	14
Curlleaf Mountain Mahogany	3
Low Sagebrush	8
Montane Sagebrush Steppe	6
Pinyon Juniper	3
Riparian and Wet Meadows	
California Montane Riparian	5
Great Basin Riparian	58
Wet Meadow	72

3.2.2 Ecological Departure With Climate Change

3.2.2.1.1 Predicted Future Ecological Condition – With and Without Climate Change

Ecological departure scores predicted under minimum management for the Northern Sierra's 25 ecological systems, with and without projected climate change impacts, are presented in Table 3-3. In the absence of climate change over a 50 year period, 11 systems show a predicted *improvement* (i.e., decline) in ecological departure score (reduced by five percent or greater), whereas eight show *little predicted change*, and six show a predicted *decline* in condition of five percent or greater (higher departure score).

When climate change impacts were included in the simulations, eight systems showed a decline of five percent or greater (higher departure score) as compared to their projected conditions in the absence of climate change. A total of five systems are projected to depart highly from their natural range of variability, as compared to only two systems without climate change. The two riparian systems and wet meadow systems, along with aspen-mixed conifer forest and lodgepole pine on dry sites were the systems at highest forecasted ecological departure. Conversely, three systems showed predicted *improvement* in ecological departure as compared to scores with no climate change.

The predicted ecological improvements of many systems in the absence of any active management despite climate impacts may seem counter-intuitive. The primary explanation for this result is the fact that the ecological models provided the “escape” of fires into the systems, even in the face of ongoing management for fire suppression (which is not always effective). Moreover, for some systems the climate change impacts increased the frequency of fire. The return of fire allowed many fire-dependent systems to “reset” closer to the natural range of variability – for example, to more early succession or open classes. A different analysis, with different assumptions about the likely use and effectiveness of fire suppression in the future, would have produced different results, with greater predicted departures from NRV under climate change scenarios for some forest types.

Table 3-3. Current and predicted 50-year future (under minimum management) ecological departure of ecological systems of the Northern Sierra, with and without projected climate change impacts. Ecological departure scores are classed as slightly departed from NRV (0-33%, green); moderately departed (34-66%, yellow); and highly departed (>66%, red).

Ecological System	Acres	Current Condition	Future Condition without CC	Future Condition with CC
Subalpine				
Alpine Shrubland	1,600	13	12	12
Lodgepole Pine - Dry	8,900	59	51	69
Lodgepole Pine - Wet	21,800	53	46	65
Red Fir - Western White Pine	379,000	37	24	27
Red Fir - White Fir	370,600	34	20	20
Subalpine Meadow	1,300	27	60	65
Subalpine Woodland	66,100	20	28	27
Mid-Elevation Forests				
Aspen-Mixed Conifer Forest	12,100	62	41	86
California Oak-Pine Forest	63,300	50	38	35
Mixed Conifer - Mesic	1,100,200	26	33	32
Ponderosa Pine - Mixed Conifer	783,600	41	44	43
Yellow Pine	889,900	54	44	45
Low-Elevation Forests				
Blue Oak-Pine Foothill Woodland	4,700	49	63	61
California Mixed Evergreen Forest	66,300	13	17	12
Xeric Shrublands				
Montane Chaparral	187,200	5	10	17
Serpentine Woodland & Chaparral	8,100	68	14	13
Mid-Elevation Eastside Shrublands/Woodlands				
Aspen Woodland	6,400	28	24	46
Big Sagebrush Shrubland	184,400	46	47	43
Curleaf Mountain Mahogany	12,600	48	33	34
Low Sagebrush	16,500	14	19	11
Montane Sagebrush Steppe	206,200	30	30	21
Pinyon Juniper	19,200	32	25	27
Riparian and Wet Meadows				
California Montane Riparian	58,100	36	50	73
Great Basin Riparian	27,300	71	73	74
Wet Meadow	108,400	83	78	89

3.2.2.1.2 High Risk Vegetation Classes

Eight of the Northern Sierra’s ecological systems are projected to experience increases in high-risk vegetation classes, and almost all of these increases occur *with or without climate change* (Table 3-4). The primary causes are: (1) increased cheatgrass in the understory of ponderosa pine, yellow pine, and three sagebrush systems; and, (2) increases in exotic forbs in the wet meadow and riparian systems. Dramatic increases are projected in California montane riparian systems’ exotic forbs. Climate change is predicted to exacerbate the high-risk classes in the wet meadow and riparian systems, by accelerating the rate of exotic forb invasion.

Table 3-4. Northern Sierra ecological systems with predicted 50-year increases in high-risk vegetation classes (under minimum management), with and without projected climate change impacts. Stress to ecological systems is ranked as: low (0%, dark green); medium (1-10%, light green); high (11-30%, yellow), and very high (>30%, red). Minimum management assumes no treatment of exotic forbs, no prescribed fire, traditional management of livestock and continued management for fire suppression.

	Current	Without Climate Change	With Climate Change
Mid-Elevation Forests			
Ponderosa Pine – Mixed Conifer	0	15	15
Yellow Pine	0	18	16
Mid-Elevation Eastside Shrublands/Woodlands			
Big Sagebrush Shrubland	14	28	28
Low Sagebrush	8	13	11
Montane Sagebrush Steppe	6	20	11
Riparian and Wet Meadows			
California Montane Riparian	5	50	73
Great Basin Riparian	58	73	75
Wet Meadow	72	78	85

3.2.2.1.3 Vegetation Shifts

Eighteen of the Northern Sierra’s 25 ecological systems are projected to experience some degree of vegetation shift or conversion over 50 years due to climate change impacts (Table 3-5). However, only two systems are projected to have conversions greater than 10% – Aspen-Mixed Conifer Forest and Aspen Woodland, both of which see a large conversion of aspen to sagebrush, chaparral or conifer.

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However, many other systems that show conversions are projected to counteract these “losses” with “gains” coming as conversions from other systems. Six percent of the existing montane sagebrush steppe, for example, is projected to convert to Wyoming sagebrush, but overall the systems gains more acres than it loses, in conversions from yellow pine.

Table 3-5. Northern Sierra ecological systems with predicted 50-year vegetation shifts due to climate change (under minimum management).

Ecological System	Conversion %
Subalpine	
Alpine Shrubland	3
Lodgepole Pine - Dry	7
Lodgepole Pine - Wet	7
Red Fir - Western White Pine	7
Red Fir - White Fir	2
Subalpine Meadow	5
Subalpine Woodland	1
Mid-Elevation Forests	
Aspen-Mixed Conifer Forest	31
California Oak-Pine Forest	1
Mixed Conifer - Mesic	3
Ponderosa Pine - Mixed Conifer	3
Yellow Pine	7
Low-Elevation Forests	
Blue Oak-Pine Foothill Woodland	1
Xeric Shrublands	
Montane Chaparral	9
Mid-Elevation Eastside Shrublands/Woodlands	
Aspen Woodland	19
Big Sagebrush Shrubland	9
Montane Sagebrush Steppe	6
Riparian and Wet Meadows	
Wet Meadow	4

3.2.2.2 Summary of Ecological Systems At-Risk from Climate Change

Five ecological systems are deemed to be at-risk due to projected climate change effects (Table 3-6). These systems and their forecasted conditions after 50 years are:

- **Aspen-Mixed Conifer Forest:** 12,100 acres, found almost exclusively on the eastside. Forecasted 86% ecological departure (highly departed) with climate change, versus only 51% (moderately departed) without climate change. Much of this increased departure is due to a 31% predicted vegetation conversion to montane sagebrush, chaparral and conifer forest with no aspen.
- **Aspen Woodland:** 6,400 acres, found solely on the eastside. Forecasted 19% vegetation conversion to montane sagebrush and chaparral.
- **California Montane Riparian:** 58,100 acres, found on both the eastside and westside. Forecasted 73% high-risk vegetation classes, versus 50% without climate change.
- **Lodgepole Pine (dry):** 8,900 acres, found predominantly on the eastside. Forecasted 69% ecological departure (highly departed from NRV) with climate change, versus only 51% (moderately departed) without climate change.
- **Wet meadows:** 108,400 acres, found on both east and west sides, but more so on the eastside. Forecasted 85% high-risk vegetation classes, versus 78% without climate change.

Table 3-6. “At-Risk” Northern Sierra ecological systems over 50 years where ecological departure, high-risk vegetation, or vegetation shifts are exacerbated due to climate change (under minimum management).

Ecological System	Acres	Ecological Departure	High-Risk Vegetation	Vegetation Conversion
Subalpine				
Lodgepole Pine - Dry	8,900			
Mid-Elevation Forests				
Aspen-Mixed Conifer Forest	12,100			
Mid-Elevation Eastside Shrublands/Woodlands				
Aspen Woodland	6,400			
Riparian and Wet Meadows				
California Montane Riparian	58,100			
Wet Meadow	108,400			

3.2.2.3 Adaptation Strategies

Implementation of traditional management strategies substantially improved the resilience of the five at-risk ecosystems and their ability to adapt in the face of predicted future climate effects over 50 years. Table 3-7 shows the projected improvements achieved in the three metrics (ecological departure, high-risk vegetation, and vegetation conversion) using the above management treatments without consideration of cost (i.e., maximum management).

- **Aspen-Mixed Conifer Forest.** A combination of prescribed fire and mechanical thinning substantially improved ecological departure in 50 years as compared to minimum management, and also reduced the projected percentage of vegetation conversion. Prescribed fire treatments were front-loaded during the initial 20 year period, while thinning was conducted over the full 50 years to achieve the desired results.
- **Aspen Woodland.** A small amount of thinning over the initial 20 years produced the optimal ecological outcomes. However, little management action may be needed for aspen woodland if climate change effects are indeed minimal during the initial 20 year period, in that the system is projected to be in good condition after 20 years, and if so, is then projected to remain relatively resilient over the subsequent 30 years.
- **California Montane Riparian.** Weed inventory and weed control achieved major improvements in ecological departure and large reduction of high-risk vegetation. Floodplain restoration (e.g., pond and plug) achieved additional improvements, as did the inclusion of grazing management systems. All strategies were conducted continuously over the 50 year period to achieve desired results.
- **Lodgepole Pine (dry).** Prescribed fire conducted during the initial 20 year period improved ecological departure and reduced vegetation conversion. Like aspen woodland, this system may require little management if climate change effects are minimal during the initial 20 year period.
- **Wet Meadows.** Weed inventory, weed control, floodplain restoration, restoration of shrub-forb encroached areas, and restoration of conifer encroached areas achieved large improvements in ecological departure and dramatic reduction of high-risk vegetation. Weed management strategies were continuous over the 50 years, whereas the physical restorations strategies were front-loaded in the initial 20 years.

Table 3-7. Ecological forecasts for five at-risk Northern Sierra ecological systems over 50 years, assuming climate change impacts, under minimum management and with maximum management treatments.

BpS	Minimum Management - 50 Yrs			Maximum Management - 50 Yrs		
	Ecological Departure	High Risk Vegetation	Vegetation Conversion	Ecological Departure	High Risk Vegetation	Vegetation Conversion
Aspen-Mixed Conifer Forest (Eastside)	86	0	30	28	0	24
Aspen Woodland (Eastside)	48	0	19	25	0	8
California Montane Riparian (West & Eastside)	74	73	0	21	6	0
Lodgepole Pine - Dry (Eastside & Westside)	68	0	7	20	0	2
Wet Meadow (Eastside & Westside)	89	85	4	33	7	5

3.2.2.4 Cost-Benefit Analysis

Table 3-8 shows the projected improvements achieved using selected management treatments designed to achieve the greatest benefits for the lowest costs (i.e., streamlined management). While improvements were not as great as with the unconstrained maximum management treatments, ecological resilience was still substantially increased through improved ecological departure and reduced high-risk vegetation for all five systems, as well as reduced vegetation conversion for three systems.

Table 3-8. Ecological forecasts for five at-risk Northern Sierra ecological systems over 50 years, assuming climate change impacts, under minimum management and with “streamlined” management treatments.

Ecological System	Minimum Management - 50 Years			Streamlined Management - 50 Years		
	Ecological Departure	High Risk Vegetation	Vegetation Conversion	Ecological Departure	High Risk Vegetation	Vegetation Conversion
Aspen-Mixed Conifer Forest (Eastside)	86	0	30	42	0	26
Aspen Woodland (Eastside)	48	0	19	23	0	6
California Montane Riparian (West & Eastside)	74	73	0	29	26	0
Lodgepole Pine - Dry (Eastside & Westside)	68	0	7	31	0	2
Wet Meadow (Eastside & Westside)	89	85	4	52	45	5

The cost differential between maximum and streamlined management treatments varies considerably among the five ecological systems, as shown in Table 3-9. The cost of restoring wet meadows is the most challenging of the systems, totaling almost \$100 million dollars over 50 years, even under streamlined management.

Table 3-9. Average annual costs of maximum and streamlined management treatments for five at-risk ecological systems.

BpS	Acres	Ave. Annual Cost Maximum Mgmt	Ave. Annual Cost Streamlined Mgmt
Aspen-Mixed Conifer Forest (Eastside)	11,000	\$ 248,000	\$ 153,000
Aspen Woodland (Eastside)	6,000	\$ 3,000	\$ -
California Montane Riparian	58,000	\$ 680,000	\$ 263,000
Lodgepole Pine - Dry	9,000	\$ 60,000	\$ 40,000
Wet Meadow	108,000	\$ 4,606,000	\$ 1,944,000

Tables 3-10 through 3-14 show for each of the five at-risk ecosystems, the types and levels of management treatments, the timing of their application over an initial 20 year period and subsequent 30 year period, the approximate costs of the varied treatments, and the ecological outcomes.

Table 3-10. Types and levels of management treatments, the timing of their application over an initial 20 year period and subsequent 30 year period, the approximate costs of the varied treatments, and the ecological outcomes for Aspen-Mixed Conifer.

Strategy Worksheet	Aspen-Mixed Conifer Forest (Eastside)				11,000	acres	1000000	
Enter percentages from "Final Conditions" as a whole number								
Vegetation Class (describe) <i>typo x in left box if high-risk</i>	NRV	Current Condition	Min Mgmt - No CC - 50 yrs	Min Mgmt CC - 50 Years	Max Mgmt - 1st 20 Yrs	Max Mgmt (CC) 2nd 30 Yrs	Streamlined - 1st 20 Yrs	Streamlined - 2nd 30 Yrs
A - Early	34%	1%	16%	0%	38%	9%	27%	6%
B - Mid Closed	54%	25%	33%	2%	45%	59%	33%	40%
C - Mid Closed	11%	27%	13%	13%	11%	9%	20%	24%
D - Late Open	1%	5%	18%	27%	2%	0%	7%	3%
E - Late Closed	0%	41%	17%	27%	3%	0%	12%	1%
Montane Sagebrush				21%		18%		18%
Mixed Conifer			2%	3%	1%	0%	1%	2%
Chapparral				6%		6%		6%
Ecological Departure		62	39	86	9	28	28	42
High-Risk Classes		1	0	0	0	0	0	0
Vegetation Conversion			2	30	1	24	1	26
Total Cost			\$ -	\$ -	\$ 5,625,000	\$ 6,750,000	\$ 3,125,000	\$ 4,500,000
ROI (vs. Min. Mgmt)				-	5.2	4.9	3.2	4.7
		Enter Notes		Enter Management Strategies, Number of Acres/Year, Costs & Number of Years				
Scenarios (enter name below)	Transitions & Multipliers	RxFire	Thinning	RxFire	Thinning			
Min Mgmt - No CC - 50 yrs								
Min Mgmt CC - 50 Years								
Max Mgmt - 1st 20 Yrs		225	225					
Max Mgmt (CC) 2nd 30 Yrs				0	300			
Streamlined - 1st 20 Yrs		125	125					
Streamlined - 2nd 30 Yrs				0	200			
Cost of Strategy (net per acre)		\$ 500	\$ 750	\$ 500	\$ 750			
Number of Years		20	20	30	30			

Table 3-11. Types and levels of management treatments, the timing of their application over an initial 20 year period and subsequent 30 year period, the approximate costs of the varied treatments, and the ecological outcomes for Aspen Woodland.

Strategy Worksheet		Aspen Woodland (Eastside)				6,000 acres		1000000	
Enter percentages from "Final Conditions" as a whole number									
Vegetation Class (describe) <i>type x in left box if high-risk</i>	NRV	Current Condition	Min Mgmt - No CC - 50 yrs	Min Mgmt CC - 50 Years	Max Mgmt - 1st 20 Yrs	Max Mgmt (CC) 2nd 30 Yrs	Streamlined - 1st 20 Yrs	Streamlined - 2nd 30 Yrs	
A - Early	10%	3%	12%	3%	11%	2%	10%	2%	
B - Mid Closed	32%	12%	30%	11%	21%	19%	18%	20%	
C - Late Closed	57%	60%	36%	38%	50%	54%	52%	55%	
D- Late Open	0%	25%	21%	29%	19%	18%	19%	17%	
Montane Sagebrush		0%	0%	14%	0%	6%	0%	4%	
Chaparral				5%	0%	2%	0%	2%	
Ecological Departure		28	24	48	19	25	20	23	
High-Risk Classes		0	0	0	0	0	0	0	
Vegetation Conversion			0	19	0	8	0	6	
Total Cost			\$ -	\$ -	\$ 150,000	\$ -	\$ -	\$ -	
ROI (vs. Min. Mgmt)				-	33.3	-	-	-	
Enter Notes Enter Management Strategies, Number of Acres/Year, Costs & Number of Years									
Scenarios (enter name below)	Transitions & Multipliers	RxFire	Thinning	RxFire	Thinning				
Min Mgmt - No CC - 50 yrs									
Min Mgmt CC - 50 Years									
Max Mgmt - 1st 20 Yrs		0	10						
Max Mgmt (CC) 2nd 30 Yrs				0	0				
Streamlined - 1st 20 Yrs		0	0						
Streamlined - 2nd 30 Yrs				0	0				
Cost of Strategy (per acre)		\$ 500	\$ 750	\$ 500	\$ 750				
Number of Years		20	20	30	30				

Table 3-12. Types and levels of management treatments, the timing of their application over an initial 20 year period and subsequent 30 year period, the approximate costs of the varied treatments, and the ecological outcomes for California Montane Riparian.

Strategy Worksheet		California Montane Riparian				58,000	acres	1000000
Enter percentages from "Final Conditions" as a whole number								
Vegetation Class (describe) <i>type x in left box if high-risk</i>	NRV	Current Condition	Min Mgmt - No CC - 50 yrs	Min Mgmt CC - 50 Years	Max Mgmt - 1st 20 Yrs	Max Mgmt (CC) 2nd 30 Yrs	Streamlined - 1st 20 Yrs	Streamlined - 2nd 30 Yrs
A - Early	10%	1%	5%	4%	9%	24%	8%	14%
B - Mid	45%	18%	13%	9%	30%	47%	22%	33%
C - Late	45%	74%	30%	13%	59%	24%	53%	28%
<input checked="" type="checkbox"/> DES		5%	5%	3%	0%	0%	6%	5%
<input checked="" type="checkbox"/> EXF			36%	65%	1%	2%	6%	12%
<input checked="" type="checkbox"/> SFEnc			6%	3%	1%	4%	4%	6%
Fenced								
<input checked="" type="checkbox"/> Conifer			3%	2%	0%	0%	1%	3%
Ecological Departure		36	51	74	16	21	25	29
High-Risk Classes		5	50	73	2	6	17	26
Vegetation Conversion								
Total Cost			\$ -	\$ -	\$ 14,000,000	\$ 42,800,000	\$ 1,750,000	\$ 11,400,000
ROI (vs. Min. Mgmt)				-	5.9	1.7	33.7	4.0
		Enter Notes		Enter Management Strategies, Number of Acres/Year, Costs & Number of Years				
Scenarios (enter name below)	Transitions & Multipliers	Weed Inventory	Exotic Control	Floodplain Restoration	Grazing Systems	Weed Inventory	Exotic Control	
Min Mgmt - No CC - 50 yrs								
Min Mgmt CC - 50 Years								
Max Mgmt - 1st 20 Yrs		2000	1000	150	10000			
Max Mgmt (CC) 2nd 30 Yrs		3000	2000	150	10000	3200	2400	
Streamlined - 1st 20 Yrs		500	250	0	0			
Streamlined - 2nd 30 Yrs						1600	1200	
Cost of Strategy (per acre)		\$ 50	\$ 250	\$ 2,000	\$ 5	\$ 50	\$ 250	

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Table 3-13. Types and levels of management treatments, the timing of their application over an initial 20 year period and subsequent 30 year period, the approximate costs of the varied treatments, and the ecological outcomes for dry Lodgepole Pine.

Strategy Worksheet		Lodgepole Pine - Dry			9,000 acres		1000000	
Enter percentages from "Final Conditions" as a whole number								
Vegetation Class (describe) <i>type x in left box if high-risk</i>	NRV	Current Condition	Min Mgmt - No CC - 50 yrs	Min Mgmt CC - 50 Years	Max Mgmt - 1st 20 Yrs	Max Mgmt (CC) 2nd 30 Yrs	Streamlined - 1st 20 Yrs	Streamlined - 2nd 30 Yrs
A - Early	20%	1%	6%	0%	48%	0%	33%	0%
B - Mid Closed	0%	3%	1%	1%	2%	2%	2%	1%
C - Mid Open	50%	11%	13%	2%	21%	57%	16%	39%
D - Late Open	26%	70%	52%	55%	20%	27%	33%	37%
E - Late Closed	4%	14%	27%	35%	9%	12%	16%	20%
Red Fir				4%		1%		1%
Mixed Conifer				3%		1%		1%
Ecological Departure		58	51	68	35	20	34	31
High-Risk Classes		0	0	0	0	0	0	0
Vegetation Conversion		0	0	7	0	2	0	2
Total Cost			\$ -	\$ -	\$ 3,000,000	\$ -	\$ 2,000,000	\$ -
ROI (vs. Min. Mgmt)				-	5.4	-	8.6	-
		Enter Notes		Enter Management Strategies, Number of Acres/Year, Costs & Number of Years				
Scenarios (enter name below)		Transitions & Multipliers		RxFire				
<i>Min Mgmt - No CC - 50 yrs</i>								
<i>Min Mgmt CC - 50 Years</i>								
<i>Max Mgmt - 1st 20 Yrs</i>				1,200				
<i>Max Mgmt (CC) 2nd 30 Yrs</i>				0				
<i>Streamlined - 1st 20 Yrs</i>				800				
<i>Streamlined - 2nd 30 Yrs</i>								
Cost of Strategy (per acre)				\$ 500				
Number of Years				5				

Table 3-14. Types and levels of management treatments, the timing of their application over an initial 20 year period and subsequent 30 year period, the approximate costs of the varied treatments, and the ecological outcomes for Wet Meadow.

Strategy Worksheet	Wet Meadow				108,000 acres		100,000		
Enter percentages from "Final Conditions" as a whole number									
Vegetation Class (describe) <i>type x in left box if high-risk</i>	NRV	Current Condition	Min Mgmt - No CC - 50 yrs	Min Mgmt CC - 50 Years	Max Mgmt - 1st 20 Yrs	Max Mgmt (CC) 2nd 30 Yrs	Streamlined - 1st 20 Yrs	Streamlined - 2nd 30 Yrs	
A - Early	7%	0%	1%	0%	11%	10%	6%	6%	
B - Mid Closed	73%	0%	5%	2%	54%	40%	24%	22%	
C - Late Open	20%	27%	16%	9%	27%	38%	26%	21%	
<input checked="" type="checkbox"/> DES		36%	32%	31%	3%	3%	22%	21%	
<input checked="" type="checkbox"/> EXF		0%	2%	10%	2%	2%	1%	0%	
<input checked="" type="checkbox"/> TrEnc		36%	33%	38%	0%	2%	19%	19%	
<input checked="" type="checkbox"/> AG		0%	5%	4%	0%	0%	0%	2%	
<input checked="" type="checkbox"/> SFEnc		0%	4%	2%	2%	0%	1%	3%	
Lodgepole Pine-wet				4%		5%		5%	
Ecological Departure		80	78	89	19	33	50	52	
High-Risk Classes		72	76	85	7	7	43	45	
Vegetation Conversion				4	0	5	0	5	
Total Cost			\$ -	\$ -	\$ 210,050,000	\$ 20,250,000	\$ 86,700,000	\$ 10,500,000	
ROI (vs. Min. Mgmt)				-	0.6	5.9	0.7	5.9	
Enter Notes			Enter Management Strategies, Number of Acres/Year, Costs & Number of Years						
Scenarios (enter name below)	Transitions & Multipliers	Weed Inventory	Exotic Control	Floodplain Restoration	Shrub-Forb Encroached Restoration	Tree Encroached Restoration	Weed Inventory (2nd 30 Yrs)	Exotic Control (2nd 30 yrs)	Shrub-Forb Encroached Restoration (2nd 30 Yrs)
<i>Min Mgmt - No CC - 50 yrs</i>									
<i>Min Mgmt CC - 50 Years</i>									
<i>Max Mgmt - 1st 20 Yrs</i>		300	200	5000	1000	500			
<i>Max Mgmt (CC) 2nd 30 Yrs</i>							2500	1200	500
<i>Streamlined - 1st 20 Yrs</i>		200	100	2000	800				
<i>Streamlined - 2nd 30 Yrs</i>							2000	1000	0
Cost of Strategy (per acre)		\$ 50	\$ 250	\$ 2,000	\$ 500	\$ 500	\$ 50	\$ 250	\$ 500

4 Conclusions and Recommendations

4.1 Conclusions

The best available climate projections available today suggest the Northern Sierra faces a future climate that is likely hotter, has less snowfall, more rain, and earlier snowmelt. Temperatures have been rising over the past century and shifts in vegetation patterns are already occurring. Nevertheless, the region's ecological systems have many inherent "competitive advantages" as compared to other regions in facing a different climate. These advantages include a diversity of environmental gradients (i.e., elevation, landforms, precipitation, temperature) that provide a broader "stage" for future adaptation, as well as local systems that are well adapted to tremendous annual climatic variability.

The Northern Sierra Partnership's priority areas are generally well situated for conserving the region's major habitat types in a changing future climate. These priority areas are embedded within a matrix of public lands that are legally protected from conversion to agricultural or urban land uses. Most major habitat types are well represented in the NSP priority areas, even though these areas were not selected to be representative of the entire Northern Sierra Nevada region. NSP priority areas, which comprise about 1,000,000 acres of the 5,000,000 acre region, include over 20% of the distribution for region's ten most abundant habitat types. Habitat types that are under-represented in NSP priority areas, but common to the Northern Sierra Nevada and adjacent regions, tend to occur at the periphery of the region (i.e., Ponderosa Pine–Mixed Conifer to the west, and Big Sagebrush Shrubland to the east), or have been previously noted as significant gaps on federal lands (i.e., oak woodlands in the Sierra Nevada foothills, and montane meadow in the northern Sierra Nevada) by the Sierra Nevada Ecosystem Project (<http://www.ceres.ca.gov/snep/>).

The NSP priority areas also do a good job of capturing climatic microrefugia (e.g., colder, wetter, and/or more connected landscape features) of the Northern Sierra Nevada region. The NSP priority areas capture at least 20% of the river corridors, seeps and springs, cold air drainages, and north-facing and shaded slopes. The Upper East Fork Carson River has the most diversity and highest density of microrefugia features, followed by Genessee Valley, Indian Valley, and the Middle American and Rubicon Rivers.

Biophysical setting (BpS) refugia are those places on the landscape with the highest likelihood of sustaining existing major habitat types in the face of climate change. Comparing between priority areas, the Upper East Fork Carson River includes the most refugia for the most BpS, even after normalizing by area. Genessee Valley, Upper Little Truckee River and Sierra Crest priority areas follow as the most significant areas for BpS refugia. Comparing between habitat types, potential refugia dominated the current extent for five BpS forecasts (Mixed Conifer–Mesic, Yellow Pine–East Side, Ponderosa Pine–Mixed Conifer, Subalpine Woodland, Lodgepole Pine–Dry), whereas potential climate stress dominated four BpS forecasts (Red Fir–White Fir, Lodgepole Pine–Wet, Aspen Woodland,

Aspen–Mixed Conifer). BpS types with under-represented climate refugia forecasts in current NSP priority areas include what appear to be a mix of patchy vulnerable systems (i.e., Lodgepole Pine–Wet, Lodgepole Pine–Dry, Aspen Woodland, Aspen–Mixed Conifer) and abundant systems in the East (i.e., Yellow Pine–East Side) and West stratification units (i.e., Ponderosa Pine–Mixed Conifer).

NSP priority areas by themselves may not be large enough to capture landscape-level processes such as the range shifts of species in response to climate change. It is important for the Partnership to think about the larger landscape of which each priority area is a part. Many NSP priority areas are embedded within a larger matrix of public lands that afford more opportunity for landscape-scale conservation management than lands in private or commercial ownerships. Figures 2-17 and 2-18 illustrate the idea that lands outside of the NSP priority areas may be essential to the conservation of several major habitat types as climate change alters the suitability of the northern Sierra Nevada landscape. These figures clearly show that refugia areas for some major habitat types are located outside of the NSP priority areas. Public lands cover a much larger geography than the NSP priority areas, with significant representation of most conifer habitat types. Therefore, where public lands contain adequate biophysical refugia for habitat types that are poorly represented in NSP priority areas, there is an opportunity to apply restoration and management practices, such as mechanical thinning and controlled burns, to increase the health and resilience of these habitat types and thereby assist these habitat types in making a transition to a changing climate. More specifically, forecasts of vegetation shifts in the Northern Sierra Nevada reveal that Aspen Woodland and Aspen–Mixed Conifer Forest are most vulnerable to conversion to other habitat types of sagebrush, chaparral or conifer. We are fortunate that aspen groves are widely recognized as very important to the biodiversity of conifer forest landscapes, and the focus of numerous forest restoration projects. Aspen release is widely practiced, a technique to thin encroaching conifers and release aspen trees from competition. The results of forecasted vegetation shifts reveals that land managers must continue to pay special attention to aspen grove management and restoration if we are to maintain this habitat type under a changing climate.

For ecological systems that are found to be at risk from projected future climate changes, management strategies can be deployed to substantially abate future threats, improve ecological condition, and reduce undesirable vegetation conversions. These management strategies (e.g., stream and meadow restoration, forest thinning and prescribed fire) are not unconventional treatments; indeed, many of them are already being deployed by NSP and its partners within NSP priority landscapes, such as TNC’s forest thinning and restoration at Independence Lake, TPL’s and TDLT’s meadow and riparian restoration work on the Little Truckee River, and FRLT’s meadow and riparian restoration at Genesee Valley. However, the challenge will be to implement the successful strategies in early years at a sufficient scope and scale, given the financial costs and complex political environment. Our report relies heavily upon theory and assumptions to survey potential future climate risks, but the major outcomes seem reasonable: technically feasible management strategies can be deployed to increase the resilience of at-risk systems in a changing climate.

The departure of major habitat types from a natural range of variability affirms widely held views regarding the condition of natural habitats in the Sierra Nevada (see Table 3-1). The departure analysis reveals that many conifer forest types such as Lodgepole Pine, Red Fir – White Fir, and Ponderosa Pine–Mixed Conifer are significantly departed from a natural range of variability today. This departure is likely a reflection of altered stand conditions due to decades of fire suppression and incompatible timber harvest practices of the past. The departure analysis also revealed that riparian and meadow habitats are categorized as highly departed from a natural range of variability. This high departure level is consistent with field observations and other studies showing meadow and riparian systems are in poor condition in the Northern Sierra Nevada due to erosion, channel down-cutting, loss of stream-bank vegetation, de-watering of meadows, conversion of meadows, and other threats associated with development and intensive agriculture/ranching practices.

When climate change impacts were included in simulations for departure of major habitat types, a total of five systems are projected to depart highly from their natural range of variability, as compared to only two systems without climate change. The systems with the highest forecasted ecological departure are California Montane Riparian, Great Basin Riparian, Wet Meadow, Aspen Mixed Conifer, and Lodgepole Pine–Dry. Conversely, three systems showed predicted *improvement* in ecological departure as compared to scores with no climate change: Red Fir–Western White Pine, Red Fir–White Fir, and Serpentine Woodland and Chaparral.

The predicted ecological improvements of three habitat types in the absence of any active management despite climate impacts may seem counter-intuitive. The primary explanation for this result is the fact that the ecological models provided the “escape” of fires into the systems, even in the face of ongoing management for fire suppression. Moreover, for some systems the climate change impacts increased the frequency of fire. The return of fire allowed many fire-dependent systems to “reset” closer to the natural range of variability for a habitat type. The predicted high departures for riparian, wet meadow, aspen mixed conifer, and lodgepole pine highlight the vulnerability of freshwater habitats to the impacts of a changing climate. The Sierra Nevada Ecosystem Report of 1996 identified riparian and aquatic systems as the most damaged and impaired in the Sierra Nevada. It is not surprising then, that they would be most vulnerable to changing climatic conditions, particularly since a warming of the Sierra Nevada will alter hydrologic regimes and place particularly high stress upon systems so directly linked to water. Aspen groves are also linked to water in that they always occur in sites with high water availability. The forecasted departure of lodgepole pine is an interesting result, suggesting that this conifer type is more vulnerable to the impacts of climate change than other conifer habitat types.

The implication of forecasted departure models suggest that riparian and meadow habitats remain an important focus for conservation and stewardship by the Northern Sierra Partnership. These system types are forecasted to experience the highest levels of stress and departure from a natural range of variability. Conservation efforts to ensure riparian meadows are connected to the broader landscape and to other freshwater sites will be

important. Acquisition, conservation easements and restoration are important tools to promote meadow resilience. In the face of a changing climate, these tools can be used to further several important objectives: maintain water rights and natural flow regimes; maintain connectivity between meadows and uplands; prevent habitat conversion of meadows; and, restore meadow hydro-geomorphology to optimize habitat conditions.

Another implication of the forecasted departure models is that lodgepole pine should receive additional scrutiny in the design and implementation of forest restoration projects. It may be warranted to place additional acreage of lodgepole pine into mechanical thinning and controlled burn projects, given their increasing departure levels from desired conditions in a changing climate.

Eight of the Northern Sierra's ecological systems are projected to experience increases in high-risk vegetation classes, and almost all of these increases occur with or without climate change (Table 3-4). The primary causes are: (1) increased cheatgrass in the understory of ponderosa pine, yellow pine, and three sagebrush systems; and (2) increases in exotic forbs in the wet meadow and riparian systems. Dramatic increases in exotic forbs are projected in California montane riparian systems. Climate change is predicted to exacerbate the high-risk classes in the wet meadow and riparian systems, by accelerating the rate of exotic forb invasion.

The forecasts of high risk vegetation classes indicate that a strong commitment to stewardship and land management will be necessary to combat the threat of invasive weeds in many major habitat types. This conclusion is challenging because today, elevation and cool temperature has been a natural barrier to many invasive plants. The future of terrestrial natural communities may come to resemble today's challenge of protecting aquatic natural communities. Aquatic invasive species are a major threat to lake and stream ecosystems and huge levels of resources are now being directed toward preventing and eradicating aquatic invasive species in places like Lake Tahoe and Independence Lake.

Forecasts of the aforementioned management strategies upon the highest at-risk major habitat types showed substantial improvements in projected habitat conditions under climate change for Aspen–Mixed Conifer Forest, Aspen Woodland, California Montane Riparian, and Lodgepole Pine–Dry. Continued use of traditional management strategies can have a dramatic impact in the ability of these at-risk habitat types to persist in the face of climate change. Traditional management includes mechanical thinning, controlled burns, weed prevention, weed control, floodplain restoration, habitat restoration, and livestock management. The cost of implementing these management strategies may be substantial over the vast geography of the Northern Sierra Nevada; streamlined meadow restoration was forecast at \$100 million over 50 years. An important ongoing role for the Northern Sierra Partnership will be to highlight the importance of this region and to attract public and private dollars for acquisition, restoration, and management.

Finally, this study provides useful forecasts of terrestrial vegetation under a changing climate, however, important next steps must be considered in future studies if we are to fully

understand and adapt to climate change. Aquatic systems and freshwater biodiversity urgently need climate change analyses. This study demonstrated that riparian and meadow systems are highly vulnerable to the effects of climate change. It is important to study and forecast how fishes, amphibians, insects, plants, mammals and birds that are associated with freshwater systems will respond to climate change. Independent of biomes, species are generally expected to respond to climate in unique ways, rather than tracking the responses of major habitat types; therefore, future studies of climate change should consider the individual responses of multiple (interacting) species across the landscape. Future comparisons between Sierra Nevada and surrounding ecoregions are needed to help identify the source of new species that may colonize the Sierra Nevada, as well as the potential destinations for species that need to migrate out of the Sierra Nevada because they can no longer tolerate climatic conditions. Additionally, as refinements to General Circulation Models (GCMs) eventually lead to consensus on the sign and magnitude of forecasted changes to precipitation, it will be important to revisit potential climate change impacts for the northern Sierra Nevada.

4.2 Short-Term Recommendations

The following major recommendations are offered to the Northern Sierra Partnership and The Nature Conservancy:

- The new NSP strategic plan should explicitly and prominently incorporate climate change adaptation within its priority goals and strategies. Our assessment suggests that *where* we work today in the project area is reasonably sufficient for addressing the threat of climate adaptation. *How* we work in these places may be as important to success.
- NSP Strategic Priority #1 should include conserving a network of functional landscapes that capture the region’s notable diversity of terrain and vegetation types. A new assessment of connectivity may be warranted to ensure that select land acquisition provide connectivity among major habitat types and future climatic microrefugia.
- The NSP five-year goals should include refining, implementing and demonstrating climate-adapted strategies for long-term landscape and ecosystem protection.
- NSP should continue to engage with partners to demonstrate forest, riparian and wetland restoration strategies that measurably improve ecological condition of at-risk systems and increase their resilience to a changing climate – including focal efforts to restore Aspen-Mixed Conifer forests at Independence Lake and to restore meadows and riparian systems along the Little Truckee River, Genesee Valley, and Red Clover Valley. NSP should develop and implement these strategies in ways that can be replicated at a larger-scale and should monitor the outcomes.
- NSP should seek to engage with the U.S. Forest Service to promote landscape-scale forest, aspen, and meadow restoration.

5 Acknowledgements

The Nature Conservancy and Northern Sierra Partnership are grateful for the generous support of Alan Seelenfreund and the Resources Legacy Fund – which made this analysis possible. Alan is a Trustee of the Conservancy’s California chapter and a long-time supporter of conservation in the Northern Sierra.

The authors also gratefully acknowledge contributions and/or review of this project, by anonymous reviewers, as well as the following individuals (in alphabetical order).

Franco Biondi, Professor, University of Nevada, Reno
Kori Blankenship, LANDFIRE, The Nature Conservancy
Dave Conklin, Climate Change Modeler, Conservation Biology Institute
David Edelson, Sierra Nevada Project Director, The Nature Conservancy
Jim Gaither, Jr., Ecoregional Ecologist, The Nature Conservancy
Kyle Merriam, Ecologist, Plumas National Forest, U.S. Forest Service
Jason Moghaddas, Conservation Director, Feather River Land Trust
Rich Niswonger, U.S. Geological Survey, NV
Robert Nowak, Professor, University of Nevada, Reno
Davis Prudic, retired, U.S. Geological Survey, NV
Liz Rank, Fire Learning Network, The Nature Conservancy
Hugh Safford, Regional Ecologist, Pacific Southwest Region, U.S. Forest Service
Rebecca Shaw, Director of Conservation Programs, The Nature Conservancy
Jason Sibold, Professor, Colorado State University
Jim Thorne, Department of Environmental Science and Policy, UC-Davis

6 References

- Araujo M.B., and M. New. 2006. Ensemble forecasting of species distributions. *Trends in Ecology and Evolution*. 22:42–46.
- Barrett, T.M. 2001. Models of vegetation change for landscape planning: a comparison of FETM, LANDSUM, SIMPPLLE, and VDDT. USDA Forest Service General Technical Report RMRS-GTR-76-WWW.
- Beukema, S.J., W.A. Kurz, C.B. Pinkham, K. Milosheva, and L. Frid. 2003. Vegetation dynamics development tool, user's guide, Version 4.4c. Prepared by ESSA Technologies Ltd.. Vancouver, BC, Canada, 239 p.
- Bradley, B.A. 2009. Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity. *Global Change Biology* 15: 196–208
- Brown, T.J., B.L. Hall, and A.L. Westerling. 2004. The impact of twenty-first century climate change on wildland fire danger in the western United States: An applications perspective. *Climatic Change* 62: 365–388.
- Chung, U., H.H. Seo, K.H. Hwang, B.S. Hwang, J. Choi, J.T. Lee, and J.I. Yun. 2006. Minimum temperature mapping over complex terrain by estimating cold air accumulation potential. *Agricultural and Forest Meteorology* 137:15–24.
- Cress, J.J., R. Sayre, P. Comer, and H. Warner. 2009. Terrestrial ecosystems—land surface forms of the conterminous United States. *In* U.S. Geological Survey Scientific Investigations, USGS.
- Daly, C., M. Halbleib, J.I. Smith, W.P. Gibson, M.K. Doggett, G.H. Taylor, J. Curtis, and P.P. Pasteris. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology* 28: 2031–2064.
- Dettinger, M.D., D.R. Cayan, M.K. Meyer, and A.E. Jeton. 2004. Simulated hydrologic responses to climate variations and change in the Merced, Carson, American River basins, Sierra Nevada, California, 1900-2099. *Climatic Change* 62: 283–317.
- Dobrowski, S.Z. 2010. A climatic basis for microrefugia: the influence of terrain on climate. *Global Change Biology*. doi: 10.1111/j.1365-2486.2010.02263.x.
- Forbis T.A., L. Provencher, L. Frid, and G. Medlyn. 2006. Great Basin land management planning using ecological modeling. *Environmental Management* 38: 62–83.
- Hann, W. J., and D. L. Bunnell. 2001. Fire and land management planning and implementation across multiple scales. *International Journal of Wildland Fire* 10: 389–403.
- Hannah L., G. Midgely, I. Davies, F. Davis, L. Ries, W. Thuiller, J. Thorne, C. Seo, D. Stoms, and N. Snider. 2008. Biomove – Creation of a complex and dynamic model for assessing the impacts of climate change on California vegetation. PIER Final Project Report.
- Klausmeyer, K.R., and M.R. Shaw. 2009. Climate change, habitat loss, protected areas and the climate adaptation potential of species in mediterranean ecosystems worldwide. *PLoS ONE* 4:e6392.

- Low, G., L. Provencher, and S. A. Abele. 2010. Enhanced conservation action planning: assessing landscape condition and predicting benefits of conservation strategies. *Journal of Conservation Planning* 6: 36–60.
- Lundquist, J.D., N. Pepin, and C. Rochford. 2008. Automated algorithm for mapping regions of cold-air pooling in complex terrain. *Journal of Geophysical Research* 113 (D22):D22107.
- Maurer, E.P. 2007. Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios. *Climatic Change* 82: 309–325.
- Mayer, K.E., and W.F. Laudenslayer. 1988. A guide to wildlife habitats of California. State of California, Resources Agency, Department of Fish and Game. Sacramento, CA.
- Nakicenovic, N., and R. Swart (eds). 2000. Emissions scenarios. Cambridge University Press. Cambridge, United Kingdom.
- Pennisi, E. 2009. Western U.S. forests suffer death by degrees. *Science* 323: 447.
- Provencher, L., J. Campbell, and J. Nachlinger. 2008. Implementation of mid-scale fire regime condition class mapping. *International Journal of Wildland Fire* 17: 390–406.
- Provencher, L., T. A. Forbis, L. Frid, and G. Medlyn. 2007. Comparing alternative management strategies of fire, grazing, and weed control using spatial modeling. *Ecological Modelling* 209: 249–263.
- Provencher L., G. Low, and S. Abele. 2009. Bodie Hills conservation action planning. Final Report to the Bureau of Land Management Bishop Field Office, The Nature Conservancy, <http://conserveonline.org/library/>
- Raupach, M.R., G. Marland, P. Ciais, C. Le Quéré, J.G. Canadell, G. Klepper, and C.B. Field. 2007. Global and regional drivers of accelerating CO₂ emissions. *Proceedings of the National Academy of Sciences* 104:10288.
- Rollins, M.G. 2009. LANDFIRE: A nationally consistent vegetation, wildland fire, and fuel assessment. *International Journal of Wildland Fire* 18:235–249.
- Sayre, R., P. Comer, H. Warner, and J. Cress. 2009. A new map of standardized terrestrial ecosystems of the conterminous United States: U.S. Geological Survey Professional Paper 1768, 17 p.
- Seavy, N.E., T. Gardali, G.H. Golet, F.T. Griggs, C.A. Howell, R. Kelsey, S.L. Small, J.H. Viers, and J.F. Weigand. 2009. Why climate change makes riparian restoration more important than ever: Recommendations for practice and research. *Ecological Restoration* 27: 330–338.
- Shannon, C.E. and W. Weaver. 1949. The mathematical theory of communication. The University of Illinois Press, Urbana, Illinois.
- Smith, S.D., T.E. Huxman, S.F. Zitzer, T. N. Charlet, D.C. Housman, J.S. Coleman, L.K. Fenstermaker, J.R. Seemann, and R.S. Nowak. 2000. Elevated CO₂ increases productivity and invasives species success in an arid ecosystem. *Nature* 408:79–82.
- Stronstrom, D.A. and J.R. Harrill. 2006. Ground-water recharge in the arid and semiarid southwestern United States—Climatic and geologic framework. USGS Professional Paper 1703A.

- Tausch, R. J., and R. S. Nowak. 1999. Fifty years of ecotone change between shrub and tree dominance in the Jack Springs Pinyon Research Natural Area. USDA, Forest Service Proceedings RMRS-P-00.
- Taylor, A.H., and R. M. Beaty. 2005. Climatic influences on fire regimes in the northern Sierra Nevada mountains, Lake Tahoe Basin, Nevada, USA. *Journal of Biogeography* 32: 425–438.
- Thorne, J.H., B.J. Morgan, and J. A. Kennedy. 2008. Vegetation change over sixty years in the central Sierra Nevada, California, USA. *Madrono*. 55: 223–237.
- U.S. Environmental Protection Agency, and U.S. Geological Survey. 2005. National hydrography dataset plus - NHDPlus, V1.1.
- U.S. Geological Survey. 2008. Land surface forms. USGS Rocky Mountain Geographic Science Center. Denver, Colorado.
- U.S. Geological Survey. 2008. National Elevation Dataset (NED) 1 Arc Second.
- U.S. Geological Survey. 2009. National hydrology dataset. In *The National Map*.
- Weiss, A.D. 2001. Topographic position and landforms analysis. 21st Annual ESRI User Conference, San Diego, California. Poster presentation.
- Westerling, A.L. Climate change impacts on wildfire. In *Climate change science and policy*. Schneider, Mastrandrea, and Rosencranz, eds. Island Press. *In press*.
- Westerling, A.L. and B.P. Bryant. 2008. Climate change and wildfire in California. *Climatic Change* 87: s231-249.
- Westerling, A.L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science* 313: 940–943
- Wilme, L., S.M. Goodman, and J.U. Ganzhorn. 2006. Biogeographic evolution of Madagascar's microendemic biota. *Science* 312:1063–1065.