MOKELUMNE WATERSHED AVOIDED COST ANALYSIS:

Why Sierra Fuel Treatments Make Economic Sense

The Nature Conservancy
Protecting nature. Preserving life.

Sierra Nevada Conservancy

Forest Service
U.S. Department of Agriculture

Chapter 9: Climate Change Vulnerability Assessment

9.1 Introduction

The fire and sediment modeling conducted as part of this analysis rely on historic datasets of local climate and fire behavior. However, there is significant regional, national, and global evidence that recent historic climatic conditions may not be representative of climate conditions in the next century as a result of greenhouse gas (GHG) emissions leading to rapidly increasing atmospheric CO_2 levels (ICLEI 2007). Future climatic conditions depend heavily on future GHG emissions, which are unknown, and therefore the associated impacts are difficult to predict. The observed fluctuations in both fire behavior and climate patterns over the past decade suggest that climate change has already begun, and the effects felt to date are likely the beginning of greater impacts to come.

Appropriate forest management is a decadal process and planning today's management strategies based on estimated stand conditions is critical to success. This, in combination with a need to better understand the impacts of climate change on ecosystem services and our ability to minimize those impacts, led us to perform a climate change vulnerability assessment for the Mokelumne watershed. The assessment relies on a compilation and review of scientific literature and an analysis of the available climate change projection data relevant to the area. The climatic and hydrologic changes are then applied to a collection of potential climate change impacts to determine where a fuel treatment program would be most effective. The assessment process we used is based on the ICLEI (2007) Climate Change Guide for Local Governments.

Future climatic forecasts are the result of anticipated changes in atmospheric conditions that result from GHG emissions scenarios. These scenarios are used in a suite of Global Circulation Models (GCMs), two of which we focus on in this chapter: the Parallel Climate Model (PCM) and the Geophysical Fluid Dynamics Laboratory (GFDL) Model. Hydrologic variables are projected to change in the future as a result of the combined changes in air temperature and precipitation patterns. A series of expected climate change impacts that realistically may be mitigated by fuel treatments in the Mokelumne watershed were the focus of this analysis, based on the compilation of available local and regional scientific literature.

The projected changes in climate and hydrologic variables are defined in Table 9.6 and Table 9.7, along with a relative confidence rank, supporting evidence, and descriptions of seasonal and spatial patterns, as applicable. The specified confidence level for climate and hydrologic variables is based on agreement between climate model outputs via analysis of climate change projection data available for the Mokelumne region (data available at www.caladapt.org) and an assessment of climate change studies published in the scientific literature. A series of expected climate change impacts relevant to forest, grassland, riparian, and infrastructure were identified from regional studies, with a focus on impacts for which an effective fuel treatments program could reduce the frequency and severity. Some climate change impact information relevant to the Mokelumne watershed was not available or accessible within the scope of this research, so we provide a relative measure of confidence for each vulnerability determination based on the criteria described in Table 9.1. A comprehensive list of references for this vulnerability analysis is provided at the end of the chapter.

9.2 Vulnerability Assessment Methods

Vulnerability is determined by reviewing current conditions, stressors, and the likely extent and magnitude of impacts in the region, and is based on the Integrated Regional Water Management (IRWM) checklist (DWR 2011). Climate change impact projections are often based on detailed numeric models of complex systems that use climate projections as inputs (e.g., hydrologic, ecologic, vegetation, fire). These impacts are combined with regional climate projection data and local information (e.g., topography, land use, crop values, water supply source, water quality) to form the basis for determining sensitivity and adaptive capacity. In turn, sensitivity and adaptive capacity are used to define vulnerability. Determining the sensitivity, adaptive capacity, and therefore the vulnerability of a natural system component requires a degree of subjectivity largely based on the availability of relevant literature and an understanding of cause and effect processes as they pertain to future conditions. To minimize the degree of subjectivity, we used a relative scale (from low to high) and a standardized assessment process that provides reasonable precision and accuracy. The steps taken to complete the vulnerability assessment are described generally in the sections below.

9.3 Climate Change Projections and Emissions Scenarios

Climate science and modeling have historically been limited to global estimations due to the complexities involved with smaller scale estimations. More recently, as understanding of the earth's climate has increased and computer power has advanced, both the science and the models have been applied at smaller, regional scales (e.g., Northern California). There are numerous widely accepted global climate models, each of which focuses on specific physical and chemical processes and interactions that drive climate patterns. Therefore, climate scientists must use multiple models to evaluate the full range of potential future climate patterns and trends, since there is a large amount of uncertainty in our ability to model complex and dynamic systems.

For this assessment, projections of climate and hydrologic changes were drawn from the scientific literature and researched using a suite of different climate models, including the PCM and GFDL models. Climate projections were downscaled by independent studies to better represent future conditions in California and specific regions within the state, including the Mokelumne watershed. The ability to zoom in on California and the Mokelumne watershed was achieved by using Bias Correction and Special Downscaling (BCSD) in several models through emissions scenarios developed by the California Energy Commission (available at www.caladapt.org).

Projections of climate and hydrology changes by global climate models are very sensitive to the future carbon- and/or GHG-emissions scenarios used. Emissions scenarios are plausible estimates of GHG concentrations in the atmosphere at various future years, based on assumptions about future population growth and economic development. The two most commonly used emissions scenarios are the A2 and B1 scenarios, which are widely accepted as the reasonable range of potential future emissions. Scenario A2 assumes that our society will make only minor changes to our current technologies and practices and that GHG emissions will continue to increase at the current rate, leading to an exponential increase in emissions over the next 100 years. B1 assumes a significant global reduction in worldwide GHG emissions, with global carbon emission rates peaking around 2050 and then declining back to the rates of the 1970s. For the majority of references cited in this analysis, the A2 and B1 emissions scenarios are used to bracket the high and low projections. It is possible that our true future emissions will fall somewhere in between these projections.

Climatic model results are expressed through three different measures: the shift in certain climate variables (e.g., mean annual precipitation) over decadal time scales, changes in spatial patterns (e.g., where precipitation falls across a region), and extreme-event changes (e.g., size and frequency). Changes in climate outcomes are determined by factors such as their mean and their variance, which are reported in Table 9.6 and Table 9.7. To estimate future changes in the hydrologic cycle due to climate change, we used the accepted methodology of pairing a hydrologic model with the GCMs, the results of which are reported in Table 9.7. Because of the inherent uncertainty of predicting the future, our climate model outputs have a range of uncertainty and we provide a measure of confidence associated with each projection in Table 9.1. Figure 9.1 compares recent and predicted air temperatures, according to the A2 and B1 scenarios.

Table 9.1: Climate change projections confidence ranking definitions

Confidence ranking	Description
High	General agreement of modeling studies has led to consensus in the scientific literature. Available information is directly relevant and applicable to local systems.
Moderate	Scientifically supported but consensus is not present due to lack of information, moderate differences between studies, or limitations for drawing general conclusions from limited scientific information. Accessibility or application of information to local systems may be somewhat limited.
Low	Limited information or conflicting results between studies, model outputs, or research findings. Accessibility or application of information to local systems is very limited.

9.4 Identifying Impacts

After reviewing the available local and regional scientific literature, we focused on climate change impacts that are both available and relevant to our goal of identifying the potential results of an effective fuel treatments program. These impacts, listed in Table 9.6, Table 9.7, and Table 9.8, are not comprehensive but instead focus solely on wildfire and erosion events.

For the purposes of this chapter, impacts are defined as changes to the condition, function, or structure of natural and human systems in the Mokelumne watershed that result from climate change. Many impacts have already been detected on global and local scales and are expected to continue (Moser et al., 2009). The studies that identify potential impacts of climate change often use the same historic climatic data sets cited in the reporting of climate change projections in Table 9.6, thus supporting the linkages between climate, hydrology, and system impacts delineated in Table 9.6, Table 9.7, and Table 9.8.

9.4.1 Sensitivity

Sensitivity is the degree to which system components (e.g., wildfire regimes, salmonid populations, stormwater conveyance) change due to climate conditions (e.g., temperature and precipitation) or system impacts (e.g., stream temperature increases or snowmelt timing changes). If a system component will be significantly affected by future climate conditions, it is considered to be highly sensitive. Table 9.2 presents the definitions of the sensitivity scale. Factors considered when determining the degrees of sensitivity include:

- The impact's degree of exposure to climate change. For example, coastal areas are more exposed to sea-level-rise-related impacts compared to inland areas.
- The existing stressors in the system beyond climate change, and whether future climatic conditions would exacerbate these stressors. For example, the degree of urban encroachment on forests may be a stressor that promotes greater frequency of wildfire ignitions.
- Resources that may become increasingly limited, either through increased demand or reduced supply, due to climate change.
- Physical and environmental barriers that may limit the ability of a species to adapt. For example, an alpine tree's ability to adjust to warmer temperatures can be limited by elevation if it currently exists at a high elevation.

Table 9.2: Scoring definitions for sensitivity to climate change impacts

Sensitivity	Definition
High	System components are expected to respond measurably to an impact based on historical observations or modeling studies.
Moderate	The response of system components to an impact has not necessarily been measured, but based on our understanding of system function there are likely to be direct or indirect responses and it is reasonable to assume that the sensitivity is not low.
Low	System components not measurably affected by impacts and will likely not be affected by climate change.

9.4.2 Adaptive capacity

As described above, evaluating the adaptive capacity of a system is the second component to understanding the degree to which it can withstand climate change. Adaptive capacities for both natural and human systems were assessed for this analysis. To understand the adaptive capacity of natural systems, we assessed the intrinsic ability of system components to adapt without any human intervention, such as policy or management action changes. For assessment of human/economic systems, adaptive capacity assessment can include the timeframe and cost associated with actions to increase the ability to withstand climate change. In determining how adaptive a system is to climate change, the following elements are considered:

- Current level of stressors and flexibility to respond to future stressors. Has the system component adapted to historic climatic changes or inclement conditions?
- Are there any barriers (legal, physical, biological) to the system's ability to adjust in response to climate change?
- Can the system adapt quickly enough to survive the climate change expected over the next century?
- Are efforts currently underway that would increase adaptability (e.g., water conservation)?

Table 9.3: Scoring definitions for adaptive capacity to climate change impacts

Adaptability	Definition
High	System components are expected to accommodate climate changes.
Moderate	The system has some capacity to adjust and the degree of negative consequences will depend on the magnitude of individual and cumulative impacts.
Low	The system has little or no capacity to accommodate change.

9.4.3 Vulnerability

Vulnerability is a system component's susceptibility to harmful impacts due to climate change. The vulnerability of systems to specific climate change impacts is determined by combining sensitivity and adaptive capacity (see Table 9.4). System components that have high sensitivity to climate changes and a low capacity to adapt are considered to be highly vulnerable to climate change. A system component that is not sensitive to climate change but has a low ability to adapt is considered moderately vulnerable. A highly sensitive impact with a high adaptive capacity suggests that an effective fuel treatment could reduce the associated impacts to upland and riparian habitats.

Table 9.4: Vulnerability ranking matrix

		Sensitivity		
		High	*Moderate*	*Low*
Adaptive capacity	*High*	Moderate	Low	Low
	Moderate	High	Moderate	Low
	Low	High	High	Moderate

The vulnerability scores for each impact are limited by the available science and the body of information used to score sensitivity and adaptive capacity. The determinations for sensitivity and adaptive capacity include subjective evaluations and depend on the perspective by the evaluator. Therefore, our confidence in the vulnerability of each impact is also provided to put bounds on the strength of the conclusions as defined in Table 9.5.

Table 9.5: Scoring definitions for confidence of vulnerability

Confidence ranking	Description
High	General scientific agreement on the vulnerability score; the evaluation is supported by a breadth of monitoring data, modeling results, research, or best available scientific information. Available information is directly relevant and applicable to local systems.
Moderate	Scientifically supported but consensus or agreement is not present due to a lack of information and/or moderate differences between studies. Accessibility or application of information to local systems may be somewhat limited.
Low	Limited information or conflicting results between studies, model outputs, expert opinions, and/or research findings. Accessibility or application of information to local systems is very limited.

Table 9.6: Projected changes for selected climate variables in the Mokelumne watershed

Climate variable (30 yr. intervals)	*Projected change by 2100*	*Confidence ranking*	*Supporting evidence*	*Seasonal and spatial patterns*
Average annual air temperatures	Expected to increase 2.5-7.5°C above historic reference period of 1971-2000	High	Projections generally show agreement between models (data downloaded from Caladapt 2013) and are consistent with statewide projections (Cayan et al. 2009). Temperature ranges correspond to different emissions scenarios and locations within the watershed.	Projections indicate longer summers with increases of 3-9°C. Winter temperature increases are projected to be slightly lower at 2-6°C (Cayan et al. 2009).
Air temperature variability	Expected 20-30% larger standard deviation than the historic reference period of 1971-2000	High	Projections generally show agreement between models (data downloaded from Caladapt 2013) and are generally consistent with statewide projections (Cayan et al. 2009).	Increases are projected in the frequency, magnitude, and duration of heat waves (temperature that exceeds 95th percentile of region's historic record). Typically, heat waves occur in July and August, but as temperatures increase over time, heat waves are expected to occur in fall and spring months with greater frequency (Cayan et al. 2009).
Annual precipitation totals	Direction of change undetermined	Low	Climate models disagree on the directional impact of climate change on precipitation (Caladapt 2011). PCM climate models generally suggest higher annual precipitation, while GFCL models indicate less rainfall, with disagreement on which months are responsible for annual precipitation increases (Cayan et al. 2009; Thorne et al. 2012).	Total annual precipitation changes cannot be determined; however, models project less precipitation in the fall and spring, meaning a majority of the precipitation will be delivered over a shortened winter season (Cayan et al. 2009; Thorne et al. 2012). Summers are predicted to be longer and drier, while peak annual precipitation appears to shift from January to February (Flint and Flint 2012).
Precipitation variability	Direction of change undetermined	Low	Climate models disagree on the direction of change. Models indicate a high degree of inter-seasonal variability, not significantly different than the historical record and without a consistent trend for the next 100 years.	Models agree the wet season, when the predominant amount of rainfall occurs, will be shortened. Some models indicate a decrease in the annual storm count but an increase in the amount of precipitation delivered per storm (Cayan et al. 2009). Potential increase in the number of storms as well as above average rainfall has been predicted for elsewhere in the state (Flint and Flint 2012). Different climate models and scenarios consistently show reductions in May precipitation totals in the Mokelumne (data downloaded from CalAdapt 2013).

Table 9.7: Projected changes for selected hydrologic variables of the Mokelumne watershed

Hydrologic variable (30 yr. intervals)	*Projected change by 2100*	*Confidence ranking*	*Supporting evidence*	*Seasonal and spatial patterns*
Drought	Approximately 50% increase in frequency of occurrence	High	Climate models agree that precipitation will be highly variable and that a drying trend is anticipated mid-century, resulting in vulnerability to drought (Cayan et al. 2012).	Future projections indicate an increase in frequency of drought; GFDL-A2 models estimate that there will be 6 droughts over the next 70 years, followed by a multi-decadal drought at the end of the century. PCM-A2 models suggest 8 droughts over the next 90 years (Flint and Flint 2012).
Potential evapotranspiration (PET)	Increase (25-70 mm) above historic reference period of 1971-2000	High	Warming average temperatures suggest increases in annual PET. Statewide models agree in the increasing change of direction in PET (Thorne et al. 2012).	Largest changes are projected during summer months (Thorne et al. 2012).
Groundwater recharge	Decrease (6-140 mm) below historic reference period of 1971-2000	High	Statewide models agree that there will be a decrease in groundwater recharge. The prediction of decreased recharge is identified by studies that predict either an increase or a decrease in future runoff (Thorne et al. 2012).	Shorter wet seasons and earlier snowmelt, coupled with longer, drier summers and increased PET, will produce unfavorable conditions for recharge. Peak recharge shifts from January to February, with the largest recharge decrease anticipated to occur in the fall (Flint and Flint 2012).
Snowpack	Decrease (7-17mm) in April above 8000 ft.	High	Snowpack decreases are directly tied to temperature increases. As temperatures warm, snow accumulation, persistence, and volume will decrease, regardless of precipitation projections. Models and emission scenarios predict reductions of 25-90% of snow water equivalent (SWE) in the Sierras by the end of the twenty-first century (Hayhoe et al. 2004).	Snowpack changes at higher elevations draining to the Mokelumne River will primarily affect the watershed via runoff pattern changes in the spring and summer (Table 9.2). March temperatures will reduce the amount of precipitation that falls as snow (Knowles et al. 2006). Increased precipitation as rain versus snow paired, with warmer temperatures from April to June, will shift peak snowmelt to earlier in the season (Knowles et al. 2006).

Runoff variability	Increase	Low	Modeling in Northern California indicates a possible increase in the largest 10% of flows above the historical period, but ambiguous change for other percentile flow ranges (Flint and Flint 2012).	Different climate models and scenarios consistently show reductions in May precipitation totals in the Mokelumne watershed, but what the resulting impact in May runoff will be is not fully understood (CalAdapt 2011).
Annual runoff	Undetermined	Low	PCM models predict an increase in precipitation, while the GFDL model forecasts a drying trend. Runoff predictions are tied to conflicting precipitation models; as a result, PCM models predict a large increase in runoff volumes in the region while the GFDL predicts a decrease (Thorne et al. 2012). Runoff modeling by Null et al. (2010) indicates there may be between a 6.4% and 9.4 % increase in the mean annual runoff as a result of air temperature increases. The Mokelumne watershed was shown to be one of the two most sensitive in the region with respect to changes in mean annual flow, peak annual flow, and duration of low flows (Null et al. 2010)	Peak runoff has traditionally been observed during snowmelt periods, typically between April–July in California. As temperatures increase, snowmelt and peak streamflow will shift to earlier in the year (Thorne et al. 2012). Shifts to the mid-point of annual runoff timing (date by which half of the annual runoff has occurred) may be 5-6 weeks earlier in the year, coupled with a 6-9 week increase in low flow durations during the summer and fall (Null et al. 2010).

Table 9.8: Vulnerability assessment for Mokelumne watershed wildfire climate change impacts, with expected adaptation benefits of an effective fuel treatment program

Expected Impact	*Climate drivers and stressors*	*References*	*Sensitivity*	*Adaptive capacity*	*Vulnerability*	*Vulnerability confidence*	*Can the expected impact be lessened by an effective fuel treatments program?*
Increased wildfire frequency and extent	Increased air temperatures, longer summers, increased PET, increased drought frequency and persistence, earlier snow melt.	Fried et al. 2004 FRAP 2010 Flannigan et al. 2000 Westerling et al. 2006 Westerling and Bryant 2008 Lenihan et al. 2008	High	High	High	High	YES Local fire modeling indicates a significant reduction in wildfire frequency and extent can be achieved through a fuel treatments program. (See Chapter 3)
Increased wildfire intensity		Fried et al. 2004 FRAP 2010 Flannigan et al. 2000 Westerling et al. 2006 Westerling and Bryant 2008 Lenihan et al. 2008	High	High	High	High	YES Local fire modeling indicates a significant reduction in wildfire intensity in high-risk locations. (See Chapter 3)
Increased costs of fuel treatment and fire suppression		Joyce et al. 2008 Thompson et al. 2012 Prestemon et al. 2012	High	Moderate	High	Moderate	YES Increasing wildfire risks and human encroachment into forested areas results in increased costs to forest managers to minimize ignitions and damage from fires. Local fire modeling indicates the frequency, extent, and intensity of fire can be significantly reduced.
Increased tree mortality	Increased drought frequency and persistence, insect infestations, disease, wildfire regime shifts	Hansen and Weltzin 2000 Shugart 2003 Barr et al. 2010 Hood et al. 2010	High	Moderate	High	High	YES Expected impact is driven by over-dense forests; fuel treatments reduce vegetation density in lieu of regular fire occurrence.
Reduced conifer timber harvest		Hannah et al. 2011	Moderate	Moderate	Moderate	Moderate	MAYBE Timber is a critical agricultural industry in the Mokelumne watershed and strategic fuel treatments may reduce wildfire damage to future harvest trees.

Shift from needle-leafed to broad-leafed trees	Increased drought frequency and persistence, insect infestations, disease, wildfire regime shifts	Lenihan et al. 2006 Lenihan et al. 2003 FRAP 2010 Lenihan et al. 2006 PRBO 2011 Lenihan et al. 2008 Barr et al. 2010	Moderate	Moderate	Moderate	Moderate	MAYBE Vegetation pattern shifts are partly due to changes in fire disturbance, but temperature increases and other associated impacts and stressors are important drivers.
Conversion of shrublands and woodlands to grasslands		FRAP 2010 Pierson et al. 2008 Lenihan et al. 2006	Moderate	Moderate	Moderate	Moderate	
Increased flooding risk	Rainfall pattern shifts, increasing encroachment to wildlands	Moody et al. 2008 DeBano 2000 Benavides-Solorio and MacDonald 2005	Low	High	Low	Low	YES Increases in flood risk are directly associated with wildfire occurrence due to loss of infiltration and increased runoff. Fire severity and other fire related impacts can be reduced with fuel treatments.
Increased sediment loading to streams and reservoirs from erosion, landslides, and debris flows	Wildfire regime shifts, rainfall pattern shifts	Paris and Cannon 2012 DeBano 2000 Thompson et al. 2013	High	Moderate	High	High	YES Sediment loading risks are associated with wildfire regime shifts. Local fire and sediment modeling suggests a significant reduction in landslide, debris flow and hillslope erosion as a result of effective fuel treatments.
Increased risk of property and infrastructure damage	Increased drought frequency and persistence, continued fire suppression actions.	Moritz and Stephens 2008 Jones and Goodrich 2008 Laird 2013 Scott et al. 2013	High	Moderate	High	Moderate	YES Future population increases will increase encroachment to forests and greater damage with increasing wildfire risks. Land-use planning policies and an effective fuel treatments program could reduce structure loss from wildfires.

Reduced habitat extent and quality for endemic fish, amphibian, and invertebrate species	Increased droughts, reduced groundwater recharge, increased stream temperatures, loss of riparian cover, earlier snow melt, reduced summer baseflows.	Moyle et al. 2012a Moyle et al. 2012b Ekstrom and Moser 2012 PRBO 2011 NMFS 2012 Medellín-Azuara et al. 2008 Barr et al. 2010 NCIRWMP 2007	High	Low	High	High	NO Conflict between water supply, hydroelectric power, and instream habitat for aquatic species will increase in the future, as will other climate-related habitat stressors. Fire-related damage to the riparian zone can result in long-term impacts to habitat quality. Some aquatic species, including salmonids, require a narrow water temperature range, which is directly correlated to air temperatures.
Decreased terrestrial cold-water fish yields		Knapp et al. 2001 Pope et al. 2009 Moyle et al. 2012a Moyle et al. 2012b NMFS 2012 Barr et al. 2010 Medellín-Azuara et al. 2008	High	Low	High	Low	NO Fire-induced erosion will degrade spawning grounds of native fish such as lamprey, suckers, salmon, and trout that build their nests in areas of clean rocks and gravels. While fuel treatments could directly reduce wildfire-induced sediment delivery to local fisheries, other climate-related stressors will increase, specifically temperature impacts.

References

Barr, B.R., M.E. Koopman, C.D. Williams, S.J. Vynne, R. Hamilton, and B. Doppelt. 2010. *Preparing for Climate Change in the Klamath Basin. National Center for Conservation Science & Policy and The Climate Leadership Initiative*. Eugene, OR: National Center for Conservation Science & Policy, and The Climate Leadership Initiative. http://www.geosinstitute.org/images/stories/pdfs/Publications/ClimateWise/KlamathBasinCFFReport_Final_Long_20100901.pdf.

Battles, J., T. Robards, A. Das, K. Waring, J.K. Gilless, F. Schurr, J. LeBlanc, G. Biging, and C. Simon. 2006. *Climate change impact on forest resources*. Sacramento, CA: California Climate Change Center.

Benavides-Solorio J.D., and MacDonald L.H. 2005. "Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range." *International Journal of Wildland Fire*. 14: 1–18.

Cayan, D.R., A.L. Luers, G. Franco, M. Hanemann, B. Croes, and E. Vine. 2006. "Overview of the California climate change scenarios project." *Climatic Change*. 87 (S1): 1-6.

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

Cayan, D., M. Tyree, M. Dettinger, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, N. Graham, and R. Flick. 2009. *Climate Change Scenarios and Sea Level Rise Estimates for the California 2009 Climate Change Assessment*. Sacramento, CA: California Energy Commission.

Cayan, D.R., P.D. Bromirski, M. Tyree, M.D. Dettinger, and R.E. Flick. 2008. "Climate change projections of sea level extremes along the California coast." *Climatic Change*. 87 (S1): 57–73.

Chaplin ‑ Kramer R. 2012. *Climate Change and the Agricultural Sector in the San Francisco Bay Area: Changes in Viticulture and Rangeland Forage Production Due to Altered Temperature and Precipitation Patterns*. Sacramento, CA: California Energy Commission.

DeBano LF. 2000. "The role of fire and soil heating on water repellency in wildland environments: a review." *Journal of Hydrology*. 231–232: 194–206.

Ekstrom, J.A., and S.C. Moser. 2012. *Climate Change Impacts, Vulnerabilities, and Adaptation in the San Francisco Bay Area: A Synthesis of PIER Program Reports and Other Relevant Research*. Sacramento, CA: California Energy Commission.

Fire and Resource Assessment Program (FRAP). 2012. "California's Forest and Rangelands: 2010 Assessment." *Fire and Resource Assessment Program*. http://frap.fire.ca.gov/assessment2010.html.

Flannigan M.D., B.J. Stocks, and B.M. Wotton. 2000. "Forest fires and climate change." *Science of the Total Environment*. 262: 221-230.

Flint, L.E., and Flint, A.L. 2012. *Simulation of climate change in San Francisco Bay Basins, California: Case studies in the Russian River Valley and Santa Cruz Mountains*. Reston, VA: U.S. Geological Survey.

Fried, J.S., M.S. Torn, and E. Mills. 2004. "The impact of climate change on wildfire severity: A regional forecast for northern California." *Climatic Change*. 64 (1):169–191.

Fried, J.S. 2008. "Predicting the effect of climate change on wildfire behavior and initial attack success." Berkeley, CA: Lawrence Berkeley National Laboratory. http://www.escholarship.org/uc/item/9t2272wx.

Frissell, C.A. 1992. *Cumulative effects of land use on salmonid habitat on southwest Oregon streams (Ph.D. thesis)*. Corvalis, OR: Oregon State University.

Hannah, L.,C. Costello, C. Guo, L. Ries, C. Kolstad, and N. Snider. 2011. *The Impact of Climate Change on California Timberlands*. Sacramento, CA: California Energy Commission.

Hanak, E. and J. Lund. 2008. *Adapting California's Water Management to Climate Change*. San Francisco, CA: Public Policy Institute of California.

Hansen, P. and J. Weltzin. 2000. "Drought disturbance from climate change: Response of United States forests." *The Science of the Total Environment*. 262: 205-220.

Hayhoe, K. et al. 2004. "Emissions pathways, climate change, and impacts on California." *Proceedings of the National Academy of Sciences of the United States of America*. 101 (34): 12422-12427.

Hood, S.M., S.L. Smith, and D.R. Cluck. 2010. "Predicting mortality for five California conifers following wildfire." *Forest Ecology and Management*. 260: 750-762.

Independent Science Advisory Board (ISAB). 2007. *Climate Change Impacts on Columbia River Basin Fish and Wildlife*. Portland, Oregon: Northwest Power and Conservation Council.

Knapp, R.A., K.R. Matthews, and O. Sarnelle. 2001. "Resistance and resilience of alpine lake fauna to fish introductions." *Ecological Monographs*. 71: 401-421.

Larsen, I., L. MacDonald, E. Brown, D. Rough, M. Welsh, J. Pietraszek, Z. Libohova, J. Benavides-Solorio and K. Schaffrath. 2009. "Causes of post-fire runoff and erosion: Water repellency, cover, or soil sealing?" *Soil Science Society of America Journal*. 73 (4): 1393-1407.

Lenihan, J.M., R. Drapek, D. Bachelet, R. Neilson. 2003. "Climate change effects on vegetation distribution, carbon, and fire in California." *Ecological Applications*. 13(6): 1667–1681.

Lenihan, J., D. Bachelet, R. Drapek and R. Neilson. 2006. *The response of vegetation distribution, ecosystem productivity, and fire in California to future climate scenarios simulated by the MC1 dynamic vegetation model*. Sacramento, CA: California Climate Change Center, California Energy Commission. http://www.energy.ca.gov/2005publications/CEC-500-2005-191/CEC-500-2005-191-SF.PDF.

Lenihan, J.M., D. Bachelet, R. Neilson, and R. Drapek. 2008. "Simulated response of conterminous United States ecosystems to climate change at different levels of fire suppression, CO2 emission rate, and growth response to CO2." *Global and Planetary Change*. 64: 16-25.

Lisle, T.E. 1989. "Sediment transport and resulting deposition in spawning gravels, North Coast California." *Water Resource Research*. 25: 1303-1319.

Madani, K., and J.R. Lund. 2010. "Estimated impacts of climate warming on California's high-elevation hydropower." *Climatic Change*. 102 (3): 521-538.

Medellín-Azuara, J., J.J. Harou, M.A. Olivares, K. Madani, J.R. Lund, R.E. Howitt, S.K. Tanaka, M.W. Jenkins, and T. Zhu. 2008. "Adaptability and adaptations of California's water supply system to dry climate warming." *Climatic Change*. 87: S75-S90.

Melack, J.M., J. Dozier, C.R. Goldman, D. Greenland, A.M. Milner, and R.J. Naiman. 1997.

"Effects of climate change on inland waters of the Pacific Coastal Mountains and Western Great Basin of North America." *Hydrological Processes*. 11: 971-992.

Moody, J.A., D.A. Martin, S.L. Haire, and D.A. Kinner. 2008. "Linking runoff response to burn severity after a wildfire." *Hydrological Processes*. 22: 2063-2074.

Moritz, M.A., and S.L. Stephens. 2008. "Fire and sustainability: considerations for California's altered future climate." *Climatic Change*. 87: S265–S271.

Moser, S., G. Franco, S. Pittiglio, W. Chou, and D. Canyan. 2009. *The Future is Now: An Update On Climate Change Science Impacts And Response Options For California*. Sacramento, CA: California Climate Change Center.

Moyle, P.B., R.M. Quiñones, and J.D. Kiernan. 2012. *Effects of climate change on the inland fishes of California, with emphasis on the San Francisco Estuary region*. Sacramento, CA: California Energy Commission.

Moyle, P.B., J.D. Kiernan, P.K. Crain, and R.M. Quiñones. 2012. *Projected Effects of Future Climates on Freshwater Fishes of California*. Sacramento, CA: California Energy Commission.

National Marine Fisheries Service (NMFS). 2012. *Public Draft Recovery Plan for Southern Oregon/Northern California Coast Coho Salmon (Oncorhynchus kisutch).* Arcata, CA: National Marine Fisheries Service.

Null, S.E., J.H. Viers, and J.F. Mount. 2010. "Hydrologic Response and Watershed Sensitivity to Climate Warming in California's Sierra Nevada." *PLoS ONE*. 5(4): e9932.

Parise M., and S.H. Cannon. 2012. "Wildfire impacts on the processes that generate debris flows in burned watersheds." *Natural Hazards*. 61 (1): 217-227.

Peterson, D. H., I. Stewart, and F. Murphy. 2008. "Principal hydrologic responses to climatic and geologic variability in the Sierra Nevada, California." *San Francisco Estuary and Watershed Science*. 6 (1):3.

Pew Center For Climate Change. 2008. *Coal and climate change facts*. http://www.pewclimate.or g/global-warming-basics/coalfacts.cfmx.

Pierson, Jr., F.B., P.R. Kormos, and C.J. Williams. 2008. "Hydrologic and erosional impacts of pinyon and juniper encroachment into a sagebrush steppe communities of the Great Basin, USA." *Proceedings of the 15th International Congress of the International Soil and Water Conservation Organization, May 18-23, 2008*. Budapest, Hungary: The International Soil and Water Conservation Organization.

Pisias, N.G., A.C. Mix, and L. Heusser. 2001. "Millennial scale climate variability of the northeast Pacific Ocean and northwest North America based on radiolaria and pollen." *Quaternary Science Review*. 20: 1561–1576.

Pope, K. L., J. Piovia-Scott, and S. P. Lawler. 2009. "Changes in aquatic insect emergence in response to whole-lake experimental manipulations of introduced trout." *Freshwater Biology*. 54: 982-993.

PRBO Conservation Science. 2011. "Projected Effects of Climate Change in California: Ecoregional Summaries Emphasizing Consequences for Wildlife. Version 1.0." *PRBO*. http://data.prbo.org/apps/bssc/climatechange.

J.P. Prestemon, K.L. Abt, and R.J. Barbour. 2012. "Quantifying the net economic benefits of mechanical wildfire hazard treatments on timberlands of the western United States." *Forest Policy and Economics*. 21: 44–53. http://dx.doi.org/10.1016/j.forpol.2012 .02.006.

Roos, M. 2003. *The Effects of Global Climate Change on California Water Resources. Contractors Report*, Sacramento, CA: Public Interest Energy Research, California Energy Commission.

Scott, J.H., D.J. Helmbrecht, S.A. Parks, and C. Miller. 2012. "Quantifying the threat of unsuppressed wildfires reaching the adjacent wildland-urban interface on the Bridger-Teton National Forest, Wyoming." *Fire Ecology*. 8 (2): 125-142.

Seavy N.E., T. Gardali, G.H. Golet, T.F. Griggs, C. Howell, R. Kelsey, S. Small, J.H. Viers, and J. Weigand. 2009. "Why Climate Change Makes Riparian Restoration More Important than Ever: Recommendations for Practice and Research." *Ecological Restoration*. 27 (3).

Shugart, H., R. Sedjo, and B. Sohngen, 2003. *Forests and global climate change: Potential impacts on U.S. forest resources*. Washington, DC: Pew Center on Global Climate Change.

Snyder, M.A., L.C. Sloan, and J.L. Bell. 2004. "Modeled regional climate change in the hydrologic regions of California: A CO2 sensitivity study." *Journal of the American Water Resources Association*. 40: 591-601.

Snyder, M.A., L.C. Sloan, N.S. Diffenbaugh, and J.L. Bell. 2003. "Future climate change and upwelling in the California Current." *Geophysical Research Letters*. 30 (15): Art. #1823.

Thompson M.P., J. Scott, P.G. Langowski, J.W. Gilbertson-Day, J.R. Hass, and E.M., Bowne. 2012. "Assessing Watershed-Wildfire Risks on National Forest System Lands in the Rocky Mountain Region of the United States." *Water*. 5: 945-971

Thompson, M.P., N.M. Vaillant, J.R. Haas, K.M. Gebert, and K.D. Stockmann. 2013. "Quantifying the potential impacts of fuel treatments on wildfire suppression costs." *Journal of Forestry*. 111(1): 49-58.

Thorne, J., B. Ryan, L. Flint, A. Flint, and L. Thuy – N'goc. 2012. *Development and Application of Downscaled Hydroclimatic Predictor Variables for Use in Climate Vulnerability and Assessment Studies*. Sacramento, CA: California Energy Commission.

Thorne, J., J. Bjorkman, and N. Roth. 2012. *Urban Growth in California: Projecting Growth in California (2000–2050) Under Six Alternative Policy Scenarios and Assessing Impacts to Future Dispersal Corridors, Fire Threats and Climate-Sensitive Agriculture*. Sacramento, CA: California Energy Commission.

Vicuna, S., R. Leonardson, M. W. Hanemann, L.L. Dale and J. A. Dracup, 2008. "Climate Change Impacts on High Elevation Hydropower Generation in California's Sierra Nevada: A Case Study in the Upper American River." *Climatic Change*. 87 (S1): 123-137.

Westerling, A.L. 2006. "Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity." *Science*. 313 (5789): 940-943.

Westerling, A.L., and B.P. Bryant. 2008. "Climate change and wildfire in California." *Climatic Change*. 87 (S1): 231-249.

Westerling, A.L, B.P. Bryant, H.K. Preisler, T.P. Holmes, H,G. Hidalgo, T. Das, and S.R. Shrestha. 2009. *Climate Change, Growth, and California Wildfire*. Sacramento, CA: California Climate Change Center.

Mokelumne Watershed Avoided Cost Analysis: Why Sierra Fuel Treatments Make Economic Sense

Report Version 1.0

April 10, 2014

Citation Suggestion:

Buckley, M., N. Beck, P. Bowden, M. E. Miller, B. Hill, C. Luce, W. J. Elliot, N. Enstice, K. Podolak, E. Winford, S. L. Smith, M. Bokach, M. Reichert, D. Edelson, and J. Gaither. 2014. "Mokelumne watershed avoided cost analysis: Why Sierra fuel treatments make economic sense." A report prepared for the Sierra Nevada Conservancy, The Nature Conservancy, and U.S. Department of Agriculture, Forest Service. *Sierra Nevada Conservancy.* Auburn, California. Online: http://www.sierranevadaconservancy.ca.gov/mokelumne.

Disclaimer

This report is rich in data and analyses and may help support planning processes in the watershed. The data and analyses were primarily funded with public resources and are therefore available for others to use with appropriate referencing of the sources. This analysis is not intended to be a planning document.

The report includes a section on cultural heritage to acknowledge the inherent value of these resources, while also recognizing the difficulty of placing a monetary value on them. This work honors the value of Native American cultural or sacred sites, or disassociated collected or archived artifacts. This work does not intend to cause direct or indirect disturbance to any cultural resources.

Produced in cooperation with the USDA Forest Service. USDA is an equal opportunity provider and employer.

Contact Information

For More Information:

The Nature Conservancy — Protecting nature. Preserving life.	Sierra Nevada Conservancy	Forest Service, U.S. Department of Agriculture
David Edelson dedelson@tnc.org **Kristen Podolak** kpodolak@tnc.org	**Kim Carr** kim.carr@sierranevada.ca.gov **Nic Enstice** nic.enstice@sierranevada.ca.gov	**Sherry Hazelhurst** shazelhurst@fs.fed.us