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Challenges to Sierra Nevada Forests and Their Local Communities: An Observational and Modeling Perspective

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CHALLENGES TO SIERRA NEVADA FORESTS AND THEIR LOCAL COMMUNITIES: AN OBSERVATIONAL AND MODELING PERSPECTIVE

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By

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ABSTRACT

CHALLENGES TO SIERRA NEVADA FORESTS AND THEIR LOCAL COMMUNITIES: AN OBSERVATIONAL AND MODELING PERSPECTIVE

Cynthia Schmidt

Global forests are experiencing dramatic changes due to changes in climate as well as anthropogenic activities. Increased warming is causing the advancement of some species upslope and northward, while it is also causing widespread mortality due to increased drought conditions. In addition, increasing human population in mountain regions is resulting in elevated risk of human life and property loss due to larger and more severe wildfires. My research focuses on assessing the current vulnerability of forests and their communities in the Sierra Nevada, and how forests are projected to change in the future based on different climate change scenarios. In the first chapter I use Landsat satellite imagery to identify and attribute cause of forest disturbance between 1985 and 2011, primarily focusing on disturbances due to insect, diseases and drought. The change-detection algorithm, Landtrendr, was successfully used to identify forest disturbance, but identifying cause of disturbance was challenging due to the spectral similarities between disturbance types. Landtrendr was most successful in identifying disturbance due to insect, disease and drought in the San Bernardino National Forest, where there is little forest management activity. In the second chapter, I assess whether state or local land use policies in high-fire prone regions exist to reduce the vulnerability of residential developments to wildfire. Three specific land-use tools associated with reducing wildfire vulnerability are identified: (1) buffers around developments; (2) clustered developments; (3)

restricting construction on slopes greater than 25%. The study also determines whether demographic and physical characteristics of selected California counties were related to implementing land use policies related to reducing wildfire vulnerability. Results indicate that land use policies related to preventing wildfire-related losses focus on building materials, road access, water availability and vegetation management, not the three identified land-use tools. San Diego County, the county that has experienced the most devastating fires, had the highest percentage of residential developments with both clustering and buffering. The third chapter focuses on future forest conditions. I used a Dynamic Global Vegetation Model (DGVM) to assess future vegetation dynamics and productivity under changing climate and atmospheric CO_2 concentrations in the Sierra Nevada. Model results suggest that Temperate Broadleaved Evergreen Plant Functional Types (PFTs) will move upslope and eastward, replacing Temperate Needleleaved PFTs. Boreal Needleleaved Evergreen PFTs, found primarily at higher elevations, will decline dramatically as temperatures continue to increase. Gross Primary Productivity (GPP) will increase as atmospheric CO_2 concentration increases, due primarily to the increase in the more productive broadleaved PFTs. Forest ecosystems play an important role in maintaining climate stability at the regional and global scales as a vital carbon sink, so understanding the role of disturbance and climate change will be vital to both scientists and policy makers in the future.

DEDICATION

To my uncle, Chris Jarvi, and my husband Greg Schmidt, two of most enthusiastic, positive people I have ever known. They have both had enormous influences on my life and on this journey in particular. Chris, I miss you immensely.

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INTRODUCTION

Forests play a vital role as a vital carbon sink to help maintain climate stability and as a source of numerous ecosystem services. Globally, forests are experiencing dramatic changes due to changes in climate as well as anthropogenic activities. Major drivers of forest change include increasing drought, deforestation, larger and more intense wildfires, insect infestation, and increased human population in mountain regions (Adams et al. 2009; Breshears et al. 2005; McDowell et al. 2011; Westerling et al. 2006). All of these changes will alter the distribution, composition and productivity of forest ecosystems worldwide. Increasing temperatures have lengthened the growing seasons and improved forest productivity in mid- to high-latitudes but decreased precipitation in drought-prone areas has increased tree mortality and reduced forest productivity. Rising temperatures are predicted to lead to species' migrations northward and up in elevation, resulting in increased mortality in the more southern and lower portions of species' distributions (Bakkenes et al. 2002; Parmesan 2006; Penuelas and Boada 2003). Ongoing changes in climate may also account for observed increases in the frequency, intensity and spatial extent of fire and insect and disease outbreaks, with more forecasted for the future.

Western U.S. forests have become particularly vulnerable to changes in climate for a variety of reasons. Since 1925, fire suppression has increased fire intervals, and led to stand thickening and the build-up of understory fuels (Allen et al. 2002; Barbour et al. 2002; Swetnam and Baisan 2003). A warming climate, fire suppression and increased ozone emissions have resulted in marked deterioration in forest health. With predictions of continued drought coupled with fire suppression, conditions are unlikely to improve. To adapt, forest managers need to understand how forests will respond to changing climate conditions and how different management policies might ameliorate the situation. Forest managers are now actively pursuing adaptive management techniques to increase the resilience of forested ecosystems to disturbance and altered regimes (Millar et al. 2007; Stephens et al. 2010). Increasing the resiliency of forests will enable them to tolerate gradual climate changes without suffering massive tree mortality.

Considerable evidence indicates that changing climate conditions are contributing to increases in tree mortality and changing distributions across the U.S.(Allen et al. 2010; Van Mantgem et al. 2009). Large mortality events due to drought and/or insect damage have occurred in piñon-juniper woodlands in the southwest US (Allen and Breshears 1998; Floyd et al. 2009; Gaylord et al. 2013), aspen and mixed conifer forests in the Rocky Mountains (Anderegg et al. 2013; Bigler et al. 2007; DeRose and Long 2012), lodgepole pine across Rocky Mountains (Coops et al. 2009a; Logan and Powell 2001; Raffa et al. 2008), subalpine conifer forests in the Sierra Nevada (Dolanc et al. 2013; Millar et al. 2012) and mixed conifer forest in southern California (Fellows and Goulden 2012). In addition, climate-linked vegetation distribution shifts have been well documented in New Mexico (Allen and Breshears 1998), Nevada (Gworek et al. 2007), and Vermont (Beckage et al. 2008).

In addition to climate-induces changes, forests are undergoing rapid human population growth in mountainous fire-prone regions resulting in escalating costs of wildfire protection and increased risk of human life and property loss (Collins et al. 2007). This growth is occurring at a time when fires in western US forests have been increasing in size, severity and duration due to a long history of fire exclusion policies coupled with persistent drought conditions in some areas (Westerling et al. 2006). Development intensity in mountain regions typically occurs at low and medium density and tends to be more dispersed, making it challenging to defend life and property. In recent years, resources for forest management have been primarily focused on defending structures from wildfire, and not enough on managing forests for wildfire and other disturbances (Dombeck et al. 2004; Theobald and Romme 2007).

In order to understand the long-term implications of climate on forest ecosystems, dynamic global vegetation models (DGVMs) are often used. DGVMs project vegetation responses based on the interaction between vegetation dynamics and biogeochemical processes including the effects of CO_2 on projection and water-use efficiency (Prentice et al. 2000). DGVMs characterize vegetation dynamics to increase the understanding of the relationship between global carbon sink and source dynamics, atmospheric CO_2 concentrations and climate change. While these models do not take into account dispersal abilities, complex biotic interactions or human activities (Gritti et al. 2013), they do provide important insight into how vegetation patterns might change in the future.

The Sierra Nevada in California provides a unique opportunity to study a range of changing vegetation and climatic conditions. Average air temperature increases and precipitation generally decreases along a latitudinal gradient from north to south. Observed changing temperature trends include warmer winter and spring temperatures (Cayan et al. 2001). Altered precipitation patterns include shifts to rain instead of snow (Bonfils et al. 2008; Vicuna and Dracup 2007), a decline in spring snow depth over recent time, and earlier onset of spring snowmelt (Cayan et al. 2008). All of these changes are causing a variety of changes in the forest ecosystem including increased wildfire threats to human populations in high fire-prone regions. Increases in tree mortality at the lower edges of species distributions have been observed in southern California (Kelly and Goulden 2008), while *Pinus albicaulis* (Pinaceae) Engelm. (whitebark pine), a high elevation conifer is experiencing significant mortality due to beetle infestation (Millar et al. 2012). Although increases in hardwood densities at lower elevations have been observed in other regions (Beckage et al. 2008), recent studies of subalpine forest dynamics in the Sierra Nevada between 1934 and 2007 have found increases in stem density but no changes in stand composition (Dolanc et al. 2013). There is speculation that vegetation in the Sierra Nevada may be experiencing a lag effect, and that we may see larger changes in vegetation dynamics in the future.

In this dissertation, I investigate the use of remote sensing techniques to monitor forest disturbance in the Sierra Nevada as well as identify cause of disturbance, analyze land use policies pertaining to decreasing the vulnerability of residential developments to wildfire, and use a DGVM to forecast changes in vegetation distribution and productivity. This research will provide insights into current forest disturbance and land use dynamics, both of which are important for forest managers to consider for forest planning efforts. Potential changes in future vegetation dynamics and productivity are also important to consider for future forest management as well as for understanding the implications of climate change on the role of forests as vital carbon sinks.

In Chapter 1, I examine how annual Landsat time series can be used to identify and attribute cause of forest disturbance. Landtrendr, a change-detection algorithm was used to categorize forest disturbance into three different activities (1) wildfire (2) forest management and (3) insect, disease and drought, between 1985 and 2011. Developing techniques for monitoring forest disturbance over large landscapes is critical for understanding the effects of changing climate conditions in forest ecosystems. These new image processing techniques take advantage of the historical Landsat Thematic Mapper archive that exists and enable forest managers to better understand disturbance dynamics over large regions.

Chapter 2 focuses on whether land use policies exist to reduce the vulnerability of residential developments to wildfire in high fire-prone counties in California. I examine state and county land-use and development policies regarding wildfire, as well as use visual interpretation of Google Earth images to determine whether new residential subdivisions have used land use tools to reduce their vulnerability to wildfire. Those tools include (1) clustering of subdivisions; (2) buffers around subdivisions; and (3) no development on slopes > 25%. The burden of reducing wildfire vulnerability is typically on the individual homeowner by reducing the amount of vegetation surrounding their homes. Results of my research assert that local and regional land use planners must also take the responsibility to reduce wildfire vulnerability through development design and placement standards.

Chapter 3 uses a DGVM to assess future vegetation dynamics and productivity under changing climate and atmospheric CO_2 concentrations in the Sierra Nevada. While most DGVMs use coarse climate data for global assessments, my research used downscaled (800 m) climate projections. The use of downscaled climate data in DGVMs is more useful, and accurate, for regional assessments, such as the Sierra Nevada. I specifically use three different climate scenarios: (1) constant CO_2; (2) stabilizing CO_2; and (3) high level CO_2 to determine changes in Plant Functional Types (PFTs) and Gross Primary Productivity (GPP) between 2010 and 2100.

Lastly, in the concluding section, I summarize the results of each chapter as well of the implications that the results suggest will enable resource managers and land-use practitioners to respond to changing forest conditions now and in the future.

CHAPTER 1

IDENTIFYING THE CAUSES AND TEMPORAL PATTERNS OF FOREST DISTURBANCE IN THE SIERRA NEVADA USING LANDSAT TIME SERIES

Introduction

Carbon (C) budgets in North America are highly dependent on the health of forest ecosystems, yet the dynamics of disturbance within those systems are not fully understood (Van Mantgem et al. 2009). Considerable evidence indicates that changing climate conditions are contributing to dramatic increases in tree mortality in US forests (Adams et al. 2009; Allen et al. 2010; Breshears et al. 2005; McDowell et al. 2011; Van Mantgem et al. 2009). At current rates of mortality, the impacts on current and future regional C storage are likely to be dramatic but the magnitude is uncertain. Large mortality events due to droughts and/or insect damage have occurred in piñon-juniper woodlands in the Southwest US (Allen and Breshears 1998; Floyd et al. 2009; Gaylord et al. 2013), aspen and mixed conifer forests in the Rocky Mountains (Anderegg et al. 2013; Bigler et al. 2007; DeRose and Long 2012), lodgepole pine in the western mountain ranges of North America (Coops et al. 2009b; Logan and Powell 2001; Raffa et al. 2008), subalpine conifer forests in the Sierra Nevada (Dolanc et al. 2013; Millar et al. 2012), and mixed conifer forests in southern California (Fellows and Goulden 2012). Trees generally grow slowly over decades but can die much more rapidly, typically within weeks or months. As a result, extensive mortality of adult trees can result in large, rapid ecosystem changes including major shifts in vegetation distributions (Allen and Breshears 1998). As many of the ongoing changes in climate are projected to persist or intensify (Easterling et al. 2000), large mortality events are likely to become more common in the future (Allen et al. 2010). This, in turn, will result in decreased ecosystem services such as timber provision, soil creation, watershed protection and long-term forest carbon sequestration.

Forest disturbance is caused by a variety of natural events as well as anthropogenic factors including biological invasions, forest management activities (clear cutting or thinning), or other activities stemming from land use development. Wildfires, due to both humans and natural causes, have long played an important role in forest health, but have increased in size and intensity since the beginning of the 20th century. Fire suppression has resulted in increased fire intervals, stand thickening, and the build-up of understory fuels (Allen et al. 2002; Barbour et al. 2002; Swetnam and Baisan 2003). This has resulted in larger, stand-killing fires in western U.S. forests (Westerling et al. 2006). Fire exclusion policies, prolonged drought, and other factors such as pollution have worked to cause decreased forest health and increased impact of mortality events (Savage 1994).

Forest mortality patterns are both spatially and temporally very complex due to a variety of factors such as drought and heat stress, tree density, life-history traits, and biotic agents including invasive plants, insects, and disease organisms. Although mortality patterns are partially understood for arid, drought-prone regions, recent research indicates that drought-induced forest decline is occurring also in forests not normally considered at risk for drought (Choat et al. 2012). Processes such as insect outbreaks or increased competition due to increased stand density may result in complex spatial patterns of mortality at a regional scale (Lloret et al. 2004). Higher tree density drives increased competition for water and nutrients, and can result in increased insect activity, particularly during periods of xeric conditions (Allen et al. 2010; Greenwood and Weisberg 2008). However, prolonged drought can also result in extensive forest mortality independent of tree density (Floyd et al. 2009). For example, increasing temperatures are predicted to result in a five-fold increase of regional-scale forest mortality for certain species (Adams 2009). Some species are more tolerant of drought conditions than others, resulting in differential mortality rates between co-occurring tree species (Gaylord et al. 2013; Gitlin et al. 2006). Temporally, some tree species have a lagged response to drought where mortality occurs years or even decades after extreme drought events, although this varies by species and the timing and intensity of the drought (Anderegg et al. 2013; Bigler et al. 2007).

Developing techniques for monitoring tree mortality over large landscapes is critical for understanding long-term C dynamics in forest ecosystems. Currently, our ability to quantify forest mortality on a global or regional scale is limited by a lack of comprehensive information on where and when mortality events occur (Allen et al. 2010). Many studies linking climate change with forest mortality have used field-based or remote sensing techniques, or a combination of both. Field-based approaches are limited because data are typically collected in small plots and cannot include the entire spatial and temporal variation of vegetation conditions over large regions. One plot-based study found widespread mortality across all western forests due to persistent high temperatures (Van Mantgem et al. 2009). Others have used elevation gradients to examine the effects of changing climate conditions on plant distributions (Allen and Breshears 1998; Beckage et al. 2008; Kelly and Goulden 2008; Penuelas and Boada 2003). Most remote sensing studies have focused on a single die-back event on one or two tree species such as piñon-juniper (Breshears et al. 2005; Huang et al. 2010), or a single causal agent of mortality, such as bark beetles (Coops et al. 2009b; Eklundh et al. 2009; Kurz et al. 2008; Meddens et al. 2013; Meigs et al. 2011; Wulder et al. 2008). Many other remote sensing studies have focused on large-area disturbance monitoring without attributing a particular cause to the disturbance (Coops et al. 2009c; Healey et al. 2005; Masek et al. 2008; Mildrexler et al. 2007; Vogelmann et al. 2009).

The use of satellite imagery to detect and monitor landscape change is not novel, however the spatial or temporal resolution of the data is often too coarse to be useful for resource management agencies. For example, large-scale disturbance caused by insects has been detected using MODIS imagery at 250 m to 1 km spatial resolution (Verbesselt et al. 2009). New image processing techniques have recently been developed to take advantage of the historical Landsat Thematic Mapper archive that exists from approximately 1985 to 2013 (Kennedy et al. 2010; Meigs et al. 2011).

These open access data are collected up to twice monthly depending on cloud and other data quality conditions. Historically, detecting change using satellite imagery utilized two dates of imagery spaced some specified multiple number of years apart. That method is problematic, especially in dynamic forest ecosystems, because processes or large events occurring between those two years are not captured. The new techniques – such as those used herein - utilize yearly Landsat imagery to capture and characterize annual changes.

There are very few studies that have attempted to identify forest disturbance across large landscapes that include many different causal agents, primarily because of the challenges of identifying those drivers. A typical approach in identifying disturbances with satellite imagery is using some kind of index such as tasseled cap (Masek et al. 2008), NDVI (Verbesselt et al. 2009), land surface temperature disturbance index (Mildrexler et al. 2007), or NBR (Kennedy et al. 2010). These approaches, while effective in identifying disturbance, are ineffective in identifying cause primarily because the resulting index values of each type of disturbance are very similar to each other. Techniques using annual time series data from Landsat have been used recently to identify cause of disturbance by taking advantage of differing temporal and magnitude characteristics of different disturbance types. One model that uses this approach is Landtrendr, which has been used for forests in the Pacific Northwest (Cohen et al. 2010; Kennedy et al. 2010; Meigs et al. 2011).

The present study used annual Landsat time series imagery to identify and attribute cause to a variety of forest disturbances for the northern, central and southern Sierra Nevada as well as the San Bernardino National Forest in California. The primary goals were to specifically identify mortality caused by insect, disease, and drought at a spatial resolution of a 30 meter Landsat pixel, assess the accuracy of those pixel data, and then analyze the relationship of the mortality patterns with historic climate across the north-south gradient of these sites. These California forests provide a unique opportunity to study a range of changing vegetation and climatic conditions for a number of reasons. For one, average air temperature increases and precipitation generally decreases along a latitudinal gradient from north to south. Second, changing temperature trends include warmer winter and spring temperatures (Cayan et al. 2001). And, altered precipitation patterns include shifts to rain instead of snow (Bonfils et al. 2008; Vicuna and Dracup 2007), a decline in spring snow depth over recent time, and earlier onset of spring snowmelt (Cayan et al. 2008). Moreover, the forests in these montane regions provide numerous services to the state of California, including forestry, recreation, and water storage (Duane 1999).

Methods

Study Area

The Sierra Nevada is one of 10 bioregions in the state of California and is defined by specific physiographic features. The region is bounded on the west by the Central Valley, on the east by the Great Basin, on the north by the Cascades, and on the south by the Tehachapi Mountains and the Mojave Desert. The Sierra Nevada extends more than 640 km in a northwest-southeast trending axis along the eastern side of

California, and is approximately 110 km in width. Peak elevations increase gradually from north to south, and include Mt. Whitney, the highest summit in the contiguous U.S. On the west side, forest types are dominated by *Pinus ponderosa* (Pinaceae) Lawson & C. Lawson (ponderosa pine) and *Pseudotsuga menziesii* (Pinaceae) (Mirb.) Franco (douglas fir), but also include *Pinus lambertiana* (Pinaceae) Douglas (sugar pine), *Calocedrus decurrens* (Cupressaceae) (Torr.) Florin (incense cedar) and *Abies concolor* (Pinaceae) Gordon & Glend. (white fir) at lower elevations and *Abies magnifica* (Pinaceae) A. Murray bis (red fir), *Pinus contorta* (Pinaceae) ex Loudon (lodgepole pine) and *Pinus jeffreyi* (Pinaceae) Balf. (jeffrey pine) at higher elevations. The drier east side consists of *Pinus edulis* (Pinaceae) Engelm. (piñon pine), *Pinus jeffreyi* and *Pinus ponderosa*. At higher elevations are *Pinus albicaulis* (Pinaceae) Engelm. (whitebark pine). In addition to the Sierra Nevada, the study area includes the San Bernardino National Forest in southern California. The San Bernardino National Forest is approximately 5340 sq. km. in size, and part of the west-east trending Transverse Ranges. The forests primarily consist of *Pinus ponderosa, Pinus jeffreyi* , *Abies concolor*, *Pinus lambertiana* and *Calocedrus decurrens*.

The study area encompasses ten National Forests and three National Parks and has been divided into three regions for this study: (1) The Northern Sierra Nevada; (2) the Southern Sierra Nevada; and (3) the San Bernardino National Forest (Fig. 1.1). Analyses were limited to National Forests and National Parks because of the geospatial reference data available through the USFS and the National Park Service (NPS) (Table 1.1). The climate is Mediterranean-type, with warm, dry summers and cool, wet winters with almost all precipitation falling between October and April. In the Sierra Nevada, average annual precipitation ranges from less than 51 cm in the south to over 200 cm in the north. Average annual precipitation in the San Bernardino National Forest is approximately 63 cm. Due to the Sierra Nevada rain shadow, precipitation is greater on the western side than the eastern side, and primarily falls as snow above 1500 m.

In recent decades California has experienced changing precipitation and temperature patterns. Both minimum and maximum temperatures have increased, with greater warming occurring in Southern California (Cordero *et al.* 2011). In the Sierra Nevada, minimum monthly temperatures have been increasing at the rate of $0.089°\mathrm{Cyr}^{-1}$ between 1960 and 2000 (Thorne et al. 2008). Although no consistent trend in the overall amount of precipitation has been detected, a larger proportion of total precipitation is falling as rain instead of snow (Moser et al. 2008; Mote 2006; Vicuna and Dracup 2007). Current research envisions an overall increase in temperature of 2.5°C and 3% decrease in precipitation by 2060 for the Sierra Nevada (Pierce et al. 2013).

Data

Georectified, annual Landsat 5 Thematic Mapper (TM) images (28.5 m spatial resolution) were acquired from the USGS Landsat archive for the six path/rows that covered the study area from approximately 1985 to 2011 (Fig. 1.1). The images were from the July/August time frame to capture vegetation change during the peak growing season and to minimize seasonal variation. Years where clouds completely obscured the imagery were not included in the analysis (Table 1.2). Analysis was limited to coniferous forests in USFS and NPS jurisdictions. Vegetation maps and National Forest and National Park boundaries were acquired from the USFS and NPS GIS online databases (www.fs.fed.us/r5/rsl/clearinghouse/data.shtml; www.nps.gov/gis/data_info/). Data to aid in identifying cause of disturbance included fire perimeters, forest management activities, and aerial survey detection data. Wildfire and prescribed fire perimeters were acquired from the CALFIRE Fire and Resource Assessment Program (FRAP;http://frap.fire.ca.gov/data/frapgisdata-subset.php). These data originate from a multiagency effort that develops fire perimeter data for wildland fires 4 hectares or greater on federal lands. Forest management activities data were acquired from the Forest Service Activity Tracking System (FACTS) database, and USFS Aerial Detection Survey (ADS) data were acquired from the USFS Forest Health Monitoring program (http://www.fs.usda.gov/detail/r5/forest-grasslandhealth/?cid=fsbdev3_046696). Surveys are conducted during the summer and early fall each year to map forest insect and disease activity. Typically, USFS observers record areas of activity in a small aircraft using a digital sketch mapping system, and look for characteristics to distinguish tree species and attribute type of damage. Lastly, climate data, including average annual precipitation, annual minimum temperature, and annual maximum temperature (4 km spatial resolution) were acquired from the PRISM Climate Group (http://www.prism.oregonstate.edu/).

Landtrendr Disturbance Mapping

Maps of forest disturbance were generated using outputs from Landtrendr algorithms (v 12.21.11), which are described in detail by Kennedy et al. (2010). To convert radiance to reflectance, a single image was manually chosen from each stack of time series Landsat images that contained minimal haze due to cloud cover or smoke and corrected using the COST approach (Chavez 1996). All other images were normalized to that reference image using the MADCAL relative radiometric normalization (Canty et al. 2004). The Landtrendr algorithm included an automated method for cloud detection and masking. The cloud masks were verified by visually analyzing the imagery, and the cloud masking algorithm was altered if necessary. The Normalized Burn Ratio (NBR; (Key and Benson 2006), was then calculated using the image stacks. The NBR uses a ratio between the Near-Infrared band (NIR: 0.76-0.90 µm) and the Shortwave Infrared band (SWIR: 1.55-1.75 µm) to identify disturbance processes and is computed as follows:

$$\text{NBR} = (\text{NIR} - \text{SWIR} / \text{NIR} + \text{SWIR})$$

This ratio is based on the fact that healthy green vegetation reflects NIR energy, and SWIR energy is largely reflected by rock and bare soil. A healthy forest will have high NIR values and low SWIR values, resulting in a high NBR value. After a forest disturbance, the SWIR values will increase, resulting in a lower NBR value. The SWIR/NIR ratio has been used to effectively detect conifer forest damage in the northeastern, northwestern, and southwestern United States (Cohen et al. 2010; Vogelmann and Rock 1988), and British Columbia (Goodwin et al. 2010).

Landtrendr temporal segmentation algorithms were then used for the time series at each pixel to identify changing NBR values. The segmentation process smooths small changes in NBR values while retaining the larger changes over time to increase the signal to noise ratio. The process identifies NBR values that increase (regrowth), decrease (disturbance), or stay the same (no change). The resulting outputs from this process include a multiband image that identifies the year of onset of disturbance, and the magnitude and duration of disturbance for each pixel. The magnitude ranges from 1 – 100, representing the percent decrease in canopy cover. Landtrendr derives magnitude values from a simple regression model that converts the NBR values to estimates of percent vegetation cover using ground data (Kennedy et al. 2010). This regression model is based on vegetation composition and density found in the Pacific Northwest, which is often comprised of dense Douglas fir. Since vegetation composition and density is different in California, the Landtrendr algorithm was adjusted to detect a lower percent vegetation cover. The duration values range from 1 to 25 years, depending on how many years were represented in the image stack. Duration values were derived by determining the number of years of decreasing NBR values. Because Landtrendr processes entire Landsat scenes, the resulting disturbance images were clipped to Northern and Southern Sierra, and San Bernardino NF boundaries.

Identifying Causes of Disturbance

Cause of disturbance was classified into three categories: (1) fire (including wildfire and prescribed fire); (2) forest management activities; and (3) insect, disease, and drought. The Landtrendr algorithm detects spectral trajectories for each pixel which can be used to help identify the cause of disturbance (Fig. 1.2). For example, the NBR values for a clearcut area or a wildfire decrease significantly in a short period of time. On the other hand, thinning and mortality caused by drought, insect, or disease result in smaller NBR values for a longer duration. The similarities in magnitude and duration values between disturbance types required the incorporation of additional data, including wildfire perimeters, forest management, and aerial survey detection data to verify cause of disturbance.

Disturbance pixels that coincided with the wildfire and prescribed fire perimeters were selected for each year and identified as fire. Similarly, the USFS forest management data were used to identify disturbances that coincided with forest-management activities (Table 1.3). Conifer stands that experienced insect or disease mortality, but were later thinned to eliminate the dead or dying trees were excluded from the forest-management activity disturbance data. Specifically, disturbances corresponding to salvage cuts or sanitation cuts were excluded from the forest-management activities list and identified as insect and disease-caused disturbance. Although many of the forest management activity disturbances were identified using the USFS database, there were many forest management activities that occurred on USFS land by private timber companies. These activities were not documented in the

USFS database but were quite prevalent in many areas in the Sierra Nevada, particularly in the northern region.

Once the disturbance pixels corresponding to fires and forest management activities were identified, they were excluded from the remaining processing. The disturbance images contained a high percentage of scattered single pixels. Most of the scattered pixels were of short duration (two years or less) and low magnitude (25% cover or less). Previous studies have found that insect-caused disturbances, especially those caused by Mountain Pine Beetle (MPB), were evident in Landsat time series as combinations of both short- and long-term decline (Meigs *et al.* 2011). Insect, disease, or drought-caused mortality clusters were characterized by the initial formation of low magnitude, long-duration pixels, followed by high magnitude, short duration pixels as the mortality peaked. This was confirmed through visual investigation of a few known areas of MPB infestation in the Sierra Nevada (June Mountain, eastern shore of Lake Tahoe, San Bernardino NF). Within these areas, disturbances with low magnitudes but longer duration often appeared from six to eight years before a larger group of pixels with values of higher magnitude but shorter duration. Given these disturbance pixel characteristics, short duration (two years or less), and low magnitude (25 or less) pixels did not correspond with drought, insect, and disease-related disturbances, and therefore were eliminated from further analyses (Fig. 1.3).

The spatial and temporal characteristics of insect, disease, and drought-caused forest disturbance are unique compared to other types of disturbances. As described above, insect-caused disturbance often starts as a few single low magnitude, longer duration pixels, then grow into a cluster of pixels of varying magnitude and duration (Fig. 1.4). This occurs as the insects slowly attack more trees over time, resulting in a spreading cluster of dead and dying trees. Given the clustering nature of drought, insect and disease-caused disturbance over time, a process that identified clusters of disturbance pixels was used using the clump and sieve process in ERDAS Imagine (v. 11.0.4, Intergraph Corporation, Atlanta, GA). The clump function was used to identify contiguous groups of pixels using all eight neighbor pixels for connectivity. The sieve function was then used to eliminate clumps that were smaller than 20 pixels per cluster (approximately 1.8 hectares). The peak disturbance year (the year with the greatest number of disturbance pixels), average magnitude and average duration of each cluster were then calculated.

The USFS ADS database, a landscape scale, multi temporal database available for identifying forest disturbance, was used to identify disturbance caused by insect, disease, and drought. For most forests in the three regions, ADS data were available from 1993 – 2011. To identify insect, disease and drought-caused disturbances, only ADS polygons labeled as mortality due to insect, disease and drought were used (i.e., polygons with other mortality causes were avoided). Using the assumption that any disturbance clusters within the ADS polygons were associated with insect and disease-caused mortality, the ADS polygons for each year were then used to select the corresponding year-disturbance clusters. All other clusters were eliminated. Any cluster with less than 50% of pixels inside of an ADS polygon was also eliminated.

Because ADS polygons were not available before 1993, there was no method to identify prior insect-caused mortality with certainty. Instead, clusters that had the greatest number of pixels occur prior to 1993 were identified, with the assumption that these disturbance clusters might be attributed to insect, disease or drought. To identify those clusters, a histogram showing the number of pixels for each year for each cluster was produced. The year with the most pixels was considered as the peak year for that cluster. A cluster was selected if the peak year was earlier than 1993, and eliminated if the peak year was later than 1993.

Accuracy Assessment

An accuracy of the insect, disease, and drought disturbance clusters for each region was assessed by testing whether they were confused with other disturbance types. Traditional accuracy assessment requires independent reference data for the entire study area. No such reference data exist other than the ADS data, so visual image interpretation of Google Earth images was employed as an alternative first approximation. For the northern and southern Sierra Nevada, high resolution, color imagery was available for 2005-2012. For the San Bernardino NF, high resolution, color imagery was available for 2002-2012. Since there were so many insect, disease, and drought disturbance clusters for the northern and southern Sierra Nevada, a new disturbance cluster image was created using the pre-clustered image for disturbances occurring between 2005 and 2011. This image was re-clustered using only the four adjacent pixels (instead of eight), but decreasing the cluster size to five pixels. This resulted in approximately 200 clusters for each region, all of which were interpreted. Since there were many fewer disturbance clusters for the San Bernardino NF, 200 pixels were randomly selected using the Geospatial Modeling Environment program (v. 0.7.2 RC2, Spatial Ecology LLC, www.spatialecology.com/gme), and a 60-m buffer polygon was created around each point. The buffer polygon was used to interpret the Google Earth imagery between 2002 and 2011. If two polygons overlapped, only one polygon was interpreted. Google Earth imagery was used to attribute cause of disturbance to clusters and polygons. If standing, dead trees were observed then the cause was identified as insect, disease or drought. Otherwise, causes were identified as thinning, other, or unknown. Lastly, to determine how well the drought, insect and disease clusters corresponded with the aerial survey data, the total number of ADS polygons that contained disturbance pixels were calculated and compared to the total number of ADS pixels for each region.

Insect-Related Disturbance and Climate Variables

Using San Bernardino NF as a case study, the total number of drought, insect and disease pixels were summed for each year. Similarly, the annual average minimum temperature, maximum temperature, and precipitation were calculated for the region from the PRISM data. The data were compared using a time series analysis to determine if there was a relationship between disturbance and climate.

Results

Identifying Causes of Disturbance

Disturbances in the San Bernardino NF are dominated by wildfire, followed by insect, disease, and drought. Forest management activities are most common in the northern Sierra Nevada and, to a lesser extent in the southern Sierra Nevada region (Fig. 1.5). Drought, insect and disease contributed to very little of the disturbances in these regions. When comparing magnitude and duration values of the disturbance types, several have very similar values (Fig. 1.6). Wildfire, which has high magnitude but short duration impacts, is very similar to clear cuts. Prescribed fire and the remaining forest management activities have moderate mean magnitude values (between 38% - 50%), and relatively short mean duration values (between two and three years). The drought, insect and disease pixels tend to have a lower mean magnitude (38%) but longer durations (six years) compared to the other disturbances. All disturbance types, especially drought, insect and disease have high variance for both magnitude and duration of the impacts.

Accuracy Assessment

The four categories identified in the accuracy assessment were Insect and Disease (which included drought), Thinning, Other, and Unknown (Table 1.4). The “Other” category included disturbances such as clear cuts, edges of wildfires, or residential development. The “Unknown” category included areas where there were no apparent disturbances. Typically these areas had low to no canopy cover, and often occurred next to small open spaces such as meadows or rock outcrops. The highest percentage of disturbance pixels correctly identified as drought, insect and disease occurred in the San Bernardino National Forest (75%). In the northern and southern Sierra Nevada, most drought, insect and disease disturbance pixels were actually due to thinning (50% and 47%, respectively), with a high percentage of pixels that were identified as unknown (35% and 32%, respectively).

Comparing the drought, insect and disease clusters to the ADS polygons, the total percentage of ADS polygons that contained drought, insect and disease clusters ranged from 12% in the northern Sierra Nevada to 1% in the southern Sierra Nevada, and 2% in the San Bernardino National Forest. The percent agreement for each region varied annually, with the highest agreement of 47% occurring in 2003 in the northern Sierra Nevada, and 33% in 2001 in the southern Sierra Nevada. The highest percent agreement in the San Bernardino NF was 20% in 2002.

Insect-Related Disturbance and Climate Variables

A time-series analysis was performed on the relationship between drought, insect and disease disturbance clusters and climate variables for the San Bernardino NF (Fig. 1.7). The disturbance time series patterns showed moderate fluctuations in disturbances over the 26 year time period, with the exception of a dramatic peak in 2002 (6.6 km^2). Coinciding with that peak disturbance time, minimum and maximum temperature increased, and the precipitation decreased. The correlations between each of the climate variables and the disturbances were highest for maximum temperature ($r^2 = 0.62$), and moderate for precipitation ($r^2 = -0.46$). The correlation was lowest for minimum temperature ($r^2 = 0.03$), but increased to $r^2 = 0.44$, after a 1 year time-lag. The correlation of the other variables did not change after analyzing various time lags from one to 10 years.

Discussion

Results showed that Sierra Nevada forests experience disturbances from numerous causal agents with very similar temporal trajectories and intensities requiring the incorporation of ancillary data to help identify cause. Visual interpretation indicated that wildfire perimeters were very effective at identifying fire-caused disturbances from the Landtrendr results. Similarly, the forest management data acquired from the FACTS database were useful to help identify most forest management activities from the Landtrendr results. However, many of the management activities are conducted by private timber companies, which are not documented in the FACTS database. As a result, many of the management activity disturbance clusters were included with the insect, disease, and drought clusters particularly in areas such as the northern Sierra Nevada. This region experiences more forest management activities by the USFS and commercial companies because of the composition of high quality timber species compared to other California forests and differing management priorities in each forest. Therefore attributing specific causes to disturbances based on NBR pixel values is difficult without using additional ancillary data.

The Landtrendr program captures a variety of spectral trajectories to help identify cause of disturbance. Meigs *et al.* (2011) found that plots affected by insect disturbance conformed to one of four generalized spectral trajectories: short duration decline then recovery, short-then long-duration decline, long-duration decline, and long-duration decline then recovery. However, the study targeted specific plots rather than assessing disturbance conditions across a continuous landscape. The ADS data, which were used to help identify drought, insect and disease-caused mortality, are often problematic because of inconsistencies in data collection due to the subjective nature of observer ratings (Ciesla 2000). The size of the delineated areas often varies tremendously resulting in polygons that are much larger than the extent of tree mortality (Fig. 1.8). Therefore, identifying the exact location of the mortality is often difficult. Conversely, very small polygons may signify only one or two dead trees, which would be impossible to detect with the Landsat imagery. Also, the ADS data do not exist prior to 1993 in the study regions. Each forest management office will often keep record of mortality events, but those data are not maintained in a region-wide database. Because the ADS data were used to help identify insect, disease and drought disturbances in the Sierra Nevada, some disturbance events in this study may have been missed.

The results of the accuracy assessment highlighted the uncertainty stemming from forest management activities and drought, insect and disease disturbance clusters, yet also demonstrated another shortcoming of the version of Landtrendr used in this study. Over one-third of the drought, insect and disease clusters resulting from the

Landtrendr process in the southern and northern Sierra Nevada were actually areas of little to no tree cover. Landtrendr appears to be falsely identifying disturbances in some of these areas. The reasons are unclear, but this program was designed for use in Pacific Northwest forests, which consist of very high coniferous tree cover. Although the program was altered to detect lower percent tree cover, the algorithm may still have limitations in non-coniferous areas. Despite these uncertainties, Landtrendr appeared to accurately identify clusters of standing dead trees throughout the study region. The relatively high accuracy of drought, insect and disease detection in the San Bernardino NF enabled a reasonable time series comparison between the temporal disturbance patterns and climate variables.

Although there was confusion in identifying cause of disturbance due to insect, disease or drought at the pixel or cluster level, the percent of total area of each type of disturbance for each region accurately reflected the actual disturbance activities in each region. Management activities completely dominate as the cause of disturbance in the northern Sierra Nevada. Confusion between some management activities and insect, disease and drought disturbances may exist, but the FACTS database indicates that the majority of disturbances in this area are due to activities that completely remove large areas of trees. These types of disturbances typically do not get confused with insect, disease or drought disturbance. Similarly, fire, which also is not easily confused with drought, insect or disease, has dominated the San Bernardino NF landscape in recent years with some of the largest, most severe fires in California history occurring in 2003 and 2007. Therefore, high magnitude disturbances that dominate a landscape can be accurately represented through Landtrendr.

The unusually high levels of mortality that occurred among Ponderosa pine, piñon pine and white fir in the San Bernardino NF beginning in 2002 has been attributed to multi-year drought and unusually high temperatures experienced in this area from 1999 to 2003 (Fellows and Goulden 2012). Many studies have determined that there is a direct relationship between drought, increased temperatures and tree mortality (Allen et al. 2010; Breshears et al. 2009). Increasing minimum temperatures significantly increases physiological activity of trees after the normal growing season (Damesin 2003) and has direct effects on insect population dynamics by increasing insect reproduction cycles and reducing cold-induced mortality. The moderately high correlations between mean annual maximum and minimum temperatures, precipitation and drought, as well as insect and disease disturbance patterns derived from Landtrendr are consistent with these previous findings.

Conclusion

The Landtrendr process can detect drought, insect and disease disturbances most accurately in areas where there are very few forest management activities occurring, which was confirmed by the accuracy assessment. Results also indicate that the Landtrendr program results in false positive identification of drought, insect and disease disturbances in areas of low tree cover. Despite these shortcomings, the Landsat annual time series can produce regional information on forest disturbance that has been lacking in the past, but is extremely important particularly given changing climate conditions. Using Landtrendr and other similar change detection methods with imagery acquired from Landsat, we can now obtain monthly to yearly disturbance patterns and characterize those patterns in terms of magnitude and duration to help attribute causality. Accurate documentation of regional forest mortality is crucial in determining how to manage forests in the future. Although satellite imagery can provide consistent, landscape-scale observations, accurate ground information is essential to verify those observations. Currently there is no comprehensive ground monitoring system in place that specifically focuses on forest disturbance. The FIA database includes forest condition in their assessments, but does not specifically focus on disturbance.

This study focused on interannual disturbances but intra-annual changes may be equally as important. The changing timing of snow melt will have drastic changes on the phenology of tree species, which will in turn affect the timing and magnitude of mortality events. The monthly Landsat record and other imagery such as MODIS coupled with monthly climate data can provide a clearer picture of seasonal disturbance patterns across the landscape.

Although satellite imagery has been frequently used to identify forest disturbance across large areas, forest managers must identify the cause of disturbance within remote sensing images in order to better understand forest processes, and manage carbon dynamics under future climate conditions. If changing climate conditions are, in fact, causing a sharp increase in mortality events, then a better understanding of the relationship between forest mortality and climate and other factors are needed, including simultaneous impacts of ozone pollution, land-use change, and elevated CO_2.

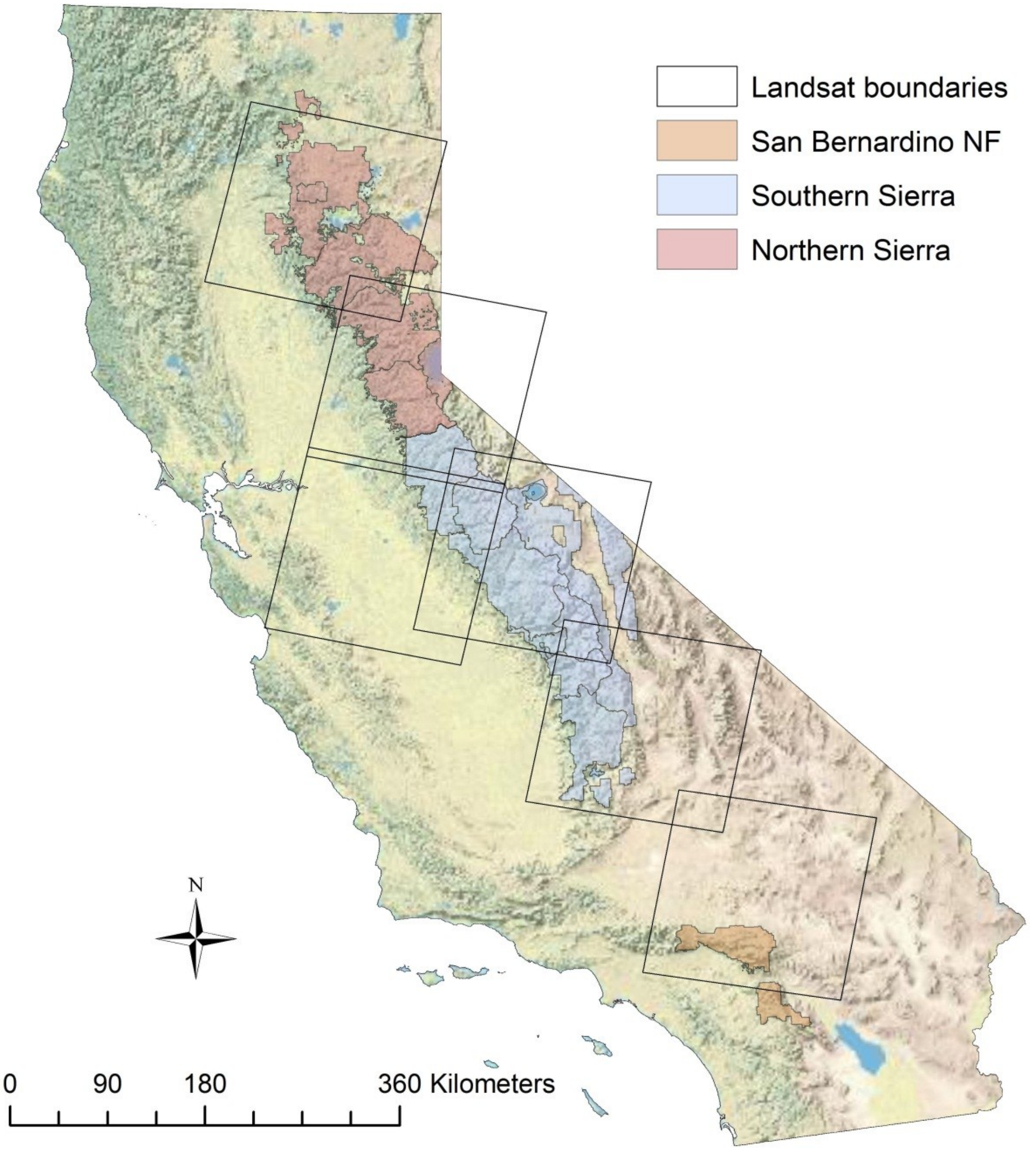

Figure 1.1. Study areas within the Sierra Nevada and Transverse mountain ranges, encompassing portions of the northern and southern Sierra Nevada and San Bernardino National Forest. Also included are the outlines of the six Landsat images used in the study.

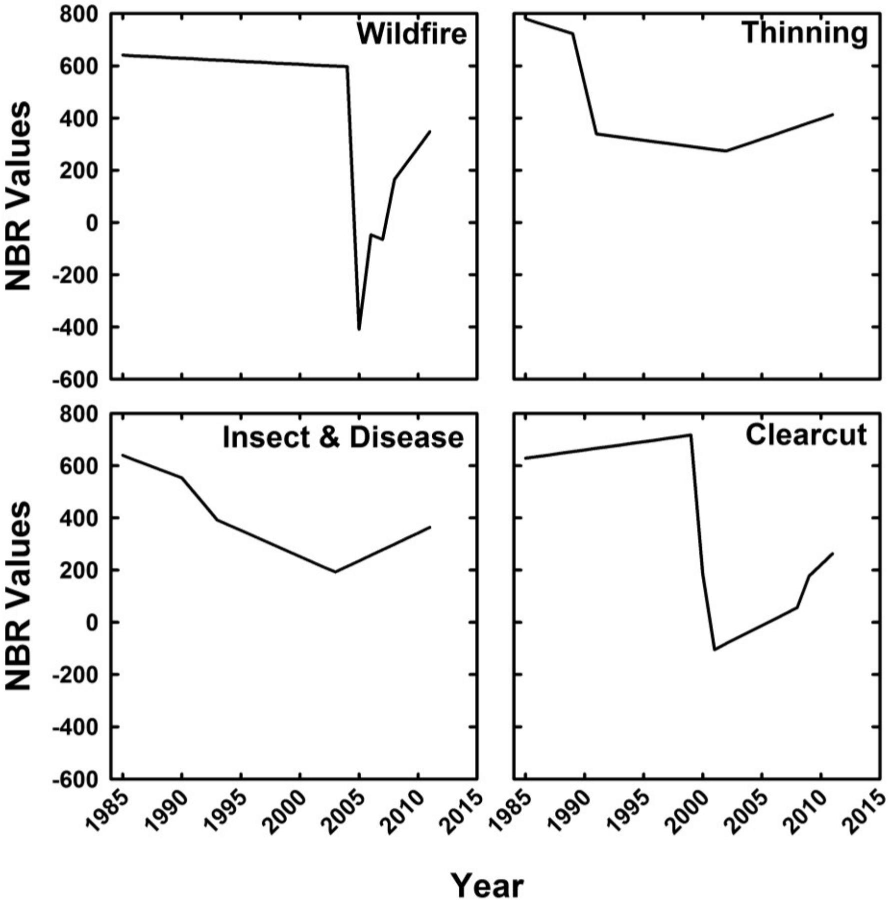

Figure 1.2. Normalized Burn Ratio (NBR; unitless) over time for the four primary sources of disturbance considered in this study.

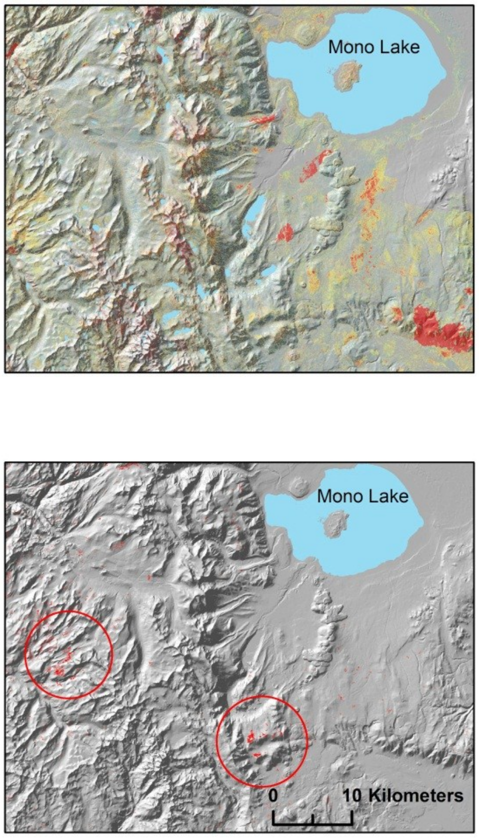

Figure 1.3. (Top) Landtrendr product showing variation in severity for a variety of disturbance types (e.g. drought, fire, insect damage and management activities), near Mono Lake, California. Colored pixels indicate most severe (red) to less severe (yellow) disturbance. (Bottom) Circles indicate where Landtrendr outputs show whitebark pine mortality on June Mountain, CA. Low intensity disturbances, fires and forest management activities have been eliminated.

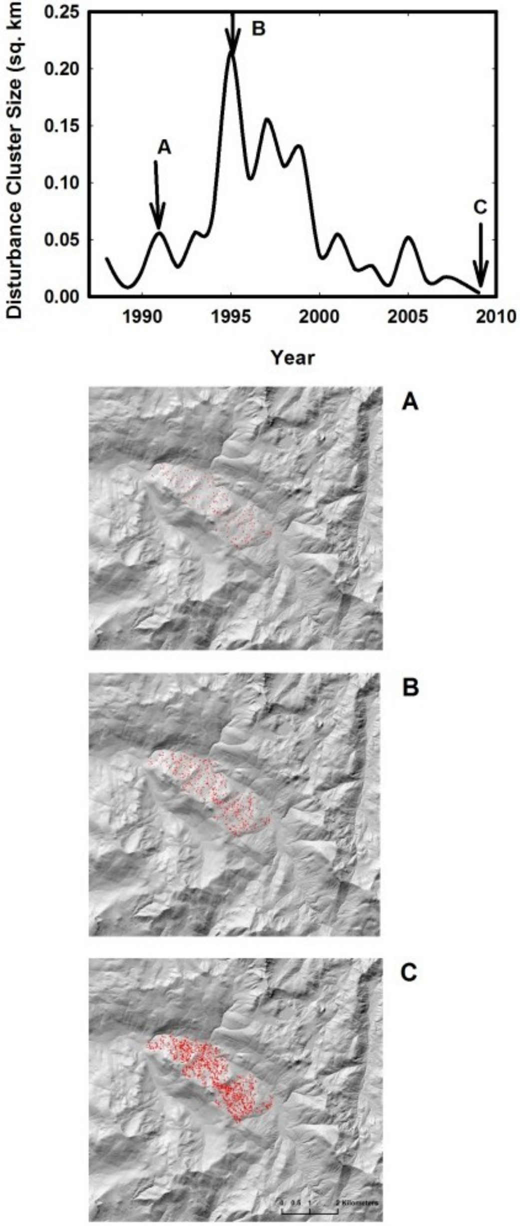

Figure 1.4. The temporal pattern of a group of disturbance clusters caused first by beetle infestation (1995), followed by a prescribed burn (1999) and detected by Landtrendr. A , B, and C show the cumulative spatial and temporal formation of the disturbance clusters. A indicates the beginning disturbances (1991), B shows the peak disturbance (1995) and C shows the cumulative disturbance pixels between 1985 and 2010. Location of disturbance clusters are in the northeast corner of the Stanislaus National Forest.

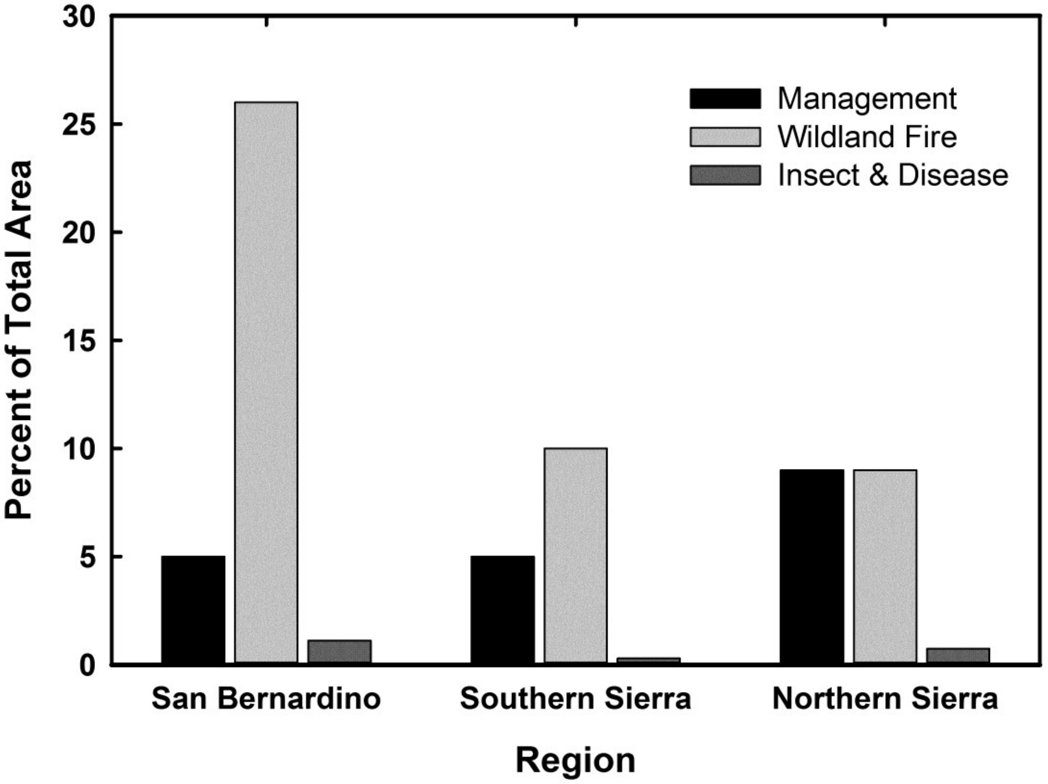

Figure 1.5. Total area disturbed for each region partitioned according to disturbance type. Total area = 2452 km^2 for the San Bernardino National Forest, 26,176 km^2 for southern Sierra Nevada, and 21,130 km^2 for northern Sierra Nevada. Fire includes wildland fire only; prescribed fire is included in Management.

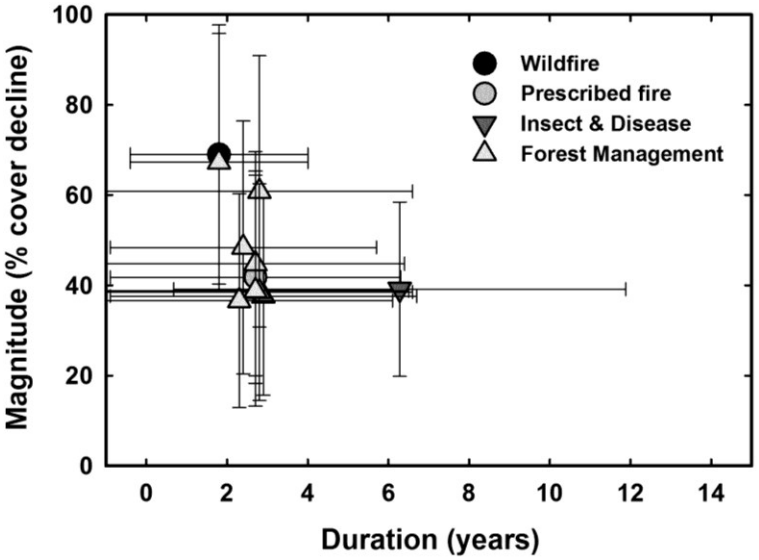

Figure 1.6. Relationship between magnitude and duration of disturbance for the southern Sierra Nevada. Magnitude is based on the percent decrease in tree cover for each 30 m Landsat pixel. Symbol is mean (± 1 SD) for all disturbance pixels from 1985 to 2011. Duration describes the time interval from the onset to the maximum of the disturbance; means and error bars as for magnitude. For Forest Management, symbols represent different regimes, including fuel management, weed treatment, clear cutting, commercial and pre-commercial thinning, and site preparation for planting and wildlife habitat restoration.

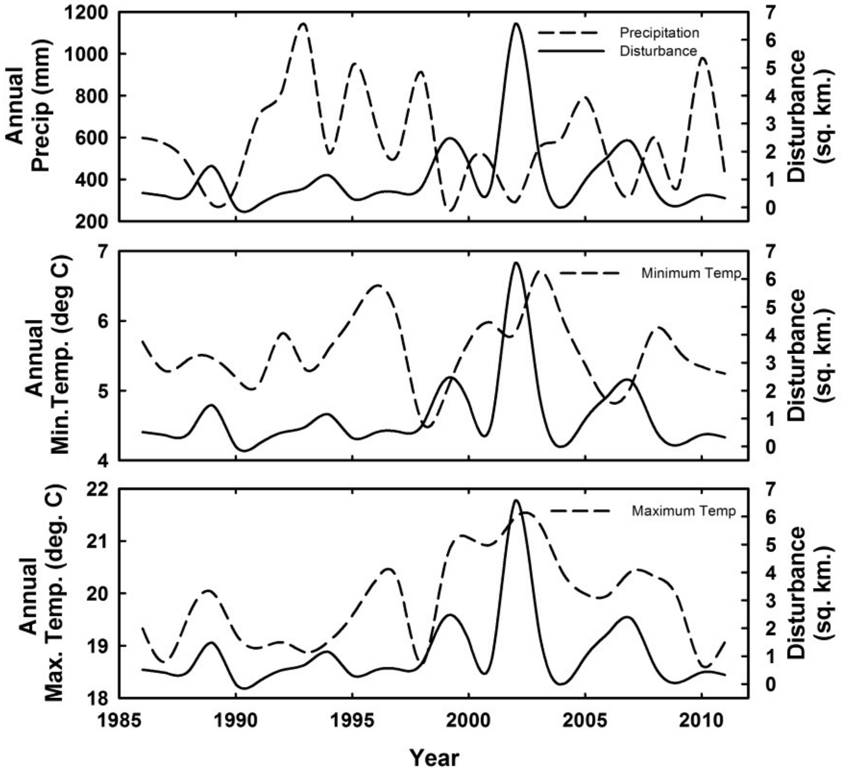

Figure 1.7. Comparison of forest mortality due to insect, disease and drought, and **A)** annual precipitation, **B)** annual minimum temperature, and **C**) annual maximum temperature, for the San Bernardino National Forest.

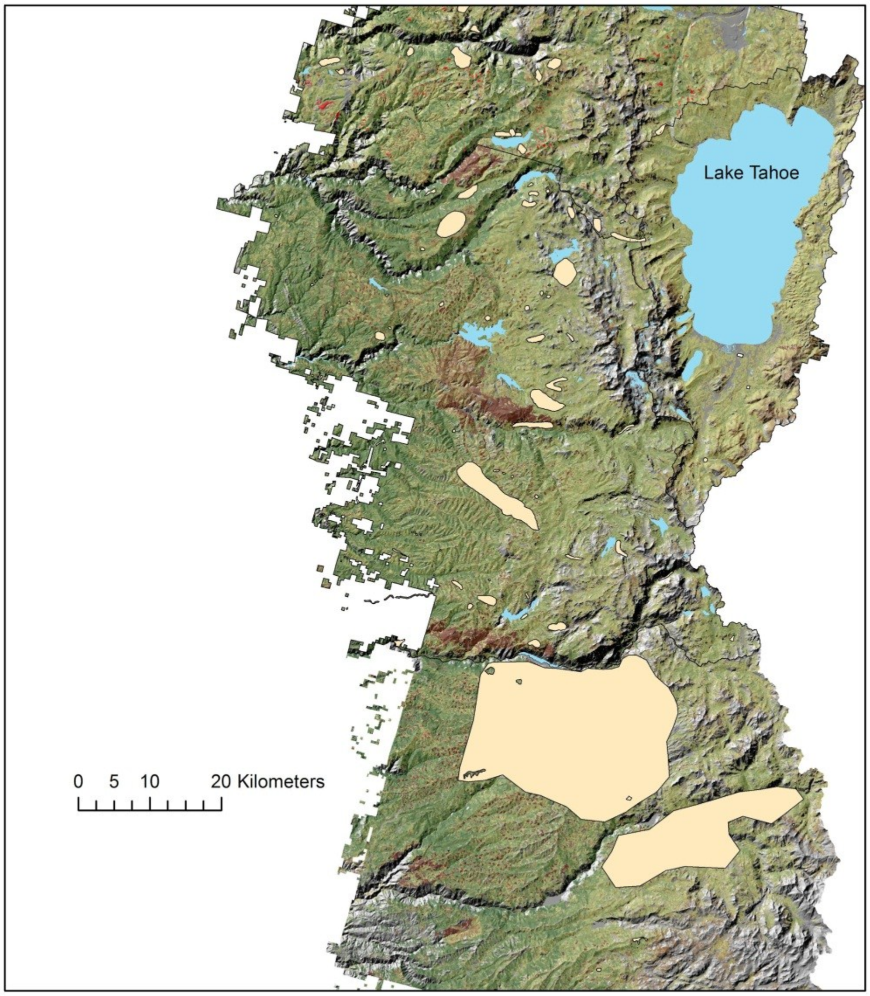

Figure 1.8. Spatial variation in polygon size indicating tree mortality (yellow polygons) due to insect and disease (combined) based on 2003 USFS Aerial Detection Survey data.

Table 1.1. Locations and areas of National Forests (NF) and National Parks (NP) that comprised the Northern and Southern Sierra Nevada and San Bernardino study regions.

Study Region	Forest Name	Total Area (sq. km)
Northern Sierra Nevada	Lassen NP	389
	Lassen NF	6017
	Plumas NF	5789
	Tahoe NF	4773
	Lake Tahoe Basin	1342
	El Dorado NF	3209
	Total	21,519
Southern Sierra Nevada	Stanislaus NF	4412
	Sequoia NF	4698
	Sierra NF	5726
	Inyo NF	8259
	Yosemite NP	3081
	Sequoia-Kings Canyon NP	3504
	Total	29,680
San Bernardino	San Bernardino NF	3270

Table 1.2. List of Landsat image path and rows, range of years used in the analysis, and years not used due to cloud cover or absence of images for the June-August time-frame.

Landsat Path/Row	Years	Skipped Years
40/36	1984-2011	1990,2004
41/35	1986-2011	1984, 1985,1990
42/34	1985-2011	1984, 1997
43/34	1984-2011	none
43/33	1985-2011	1984
44/32	1984-2011	1985,1992

Table 1.3. Forest management activities from the USFS Forest Service Activity Tracking System FACTS database.

Forest Management Activity
Fuel Management (includes burning, compacting, chipping and thinning)
Weed treatment
Cutting (including clearcutting, shelterwood cuts, and selective cuts)
Other cuts (commercial thinning, sanitation cuts, salvage cuts)
Planting (with and without site preparation)
Thinning (pre-commercial thinning and prescribed burns)
Wildlife habitat seeding
Wildlife habitat site preparation(Rx fire, thinning)

Table 1.4. Accuracy assessment for the three study regions. Total indicates the total number of drought, insect and disease clusters used in the assessment. The number of clusters and percent of total are specified for each disturbance type identified using Google Earth.

	Insect & Disease	**%**	**Thinning**	**%**	**Other**	**%**	**Unknown**	**%**	**Total**
Northern Sierra Nevada	17	9	98	50	13	7	68	35	196
Southern Sierra Nevada	40	20	96	47	2	1	65	32	203
San Bernardino NF	170	75	2	1	0	0	55	24	227

CHAPTER 2

EVALUATING LAND USE POLICIES AND PRACTICES TO REDUCE RESIDENTIAL VULNERABILITY TO WILDFIRE

Introduction

Human populations are dramatically increasing in fire-prone areas resulting in escalating costs of fighting fires and increased risk of human life and property loss (Collins and Bolin 2009). This growth is occurring at a time when fires in western U.S. forests have been increasing in size, severity and duration due to a long history of fire exclusion policies coupled with increasing temperatures and persistent drought conditions in some areas. Studies indicate projected climate changes will result in more frequent and more intense fires (Fried et al. 2004; Lenihan et al. 2003; Westerling et al. 2006). State governments, to varying degrees have established both voluntary programs and mandatory regulatory programs to decrease the vulnerability of residential development to fire. Voluntary programs include the development of Fire Wise programs to provide education and outreach activities to homeowners. Mandatory regulatory programs include enacting stringent building codes, defensible space requirements, and land use requirements. This study focuses on determining whether local land use policies exist and are being enforced to reduce the vulnerability of residential developments to wildfire in high fire prone areas in California.

The Wildland-Urban Interface (WUI) is defined as the area where structures and other human development meet or intermingle with undeveloped wildland (Radeloff et al. 2005; Stewart et al. 2007). Population growth in the WUI has increased rapidly throughout the United States and has become the primary factor influencing the management of national forests (Dombeck et al. 2004; Theobald and Romme 2007). Development density in the WUI typically occurs at low and medium density and tends to be more dispersed, making it challenging to defend structures. Homeowners in these areas often prefer high density vegetation without considering associated risks (Daniel et al. 2002). These growth patterns are exacerbating wildland fire problems through increased risk of property loss and increased cost of defending structures. Development in the WUI affects wildfires in a number of ways, including increasing the number of ignitions since humans are responsible for igniting a majority of the wildfires that burn (Keeley 2002; Syphard et al. 2007), increasing costs of protection, and limiting the options for fuel reduction since prescribed burns and other forest treatments are more difficult to implement around residential development (Bernstein 2007).

The WUI in California experienced exponential population growth over the last 30 years and has become the third-fastest growing region in the state. Of the eight million acres of WUI in California, about 5.5 million are classified by CALFIRE as high, very high, or extreme wildfire threat. 380,000 new housing units were constructed in the WUI in southern California and the Sierra Nevada during the 1990s (Hammer et al. 2007). Both push and pull factors have driven human settlement into the region including favorable attitudes towards wilderness, equating high quality of life with increased space and environmental amenities, and changes in economic status and employment trends (Duane 1999; Smith and Krannich 2000). Wildfires have increased in size and severity with 2007 being one of the worst wildfire years in California history, destroying 3079 structures and resulting in suppression costs of nearly $300 million (CalFire 2008).

Rising fire protection costs, increased threat to life and property and changing fire conditions have resulted in an urgent need to implement pre-fire mitigation strategies. Current strategies focus on mitigation of wildfire threat to residential homes in the WUI, and are grouped into four general categories: (1) vegetation management programs; (2) public education and outreach; (3) building regulations for new and existing development; and (4) land use policies to restrict the location and density of development. Vegetation management programs include the creation and maintenance of defensible space around residential structures. Defensible space is an area (typically 30-100 ft.) around homes that have been cleared of highly flammable vegetation to create a barrier between an advancing fire and the structures. Such measures have been found to be extremely effective at reducing the damage of wildfire to homes (Cohen 2000). However, residents in some areas have been mixed in their support of maintaining defensible space because it may not coincide with privacy and aesthetic preferences (McCaffrey et al. 2011). In addition, residents may resist government attempt to assert control over private property (Gillanders et al. 2008; Nelson et al. 2005; Winter et al. 2002). In California, education and outreach efforts are conducted by Fire Safe Council program which provides information and technical assistance to residents regarding maintaining defensible space, providing fire safe landscape design, fire resistant roof materials and other fire-related information. Most building regulations for minimizing wildfire damage require fire-resistant roof materials, and, in California, also fire-resistant exterior wall materials, decks and accessory buildings.

Most wildfire mitigation efforts target homeowner compliance with vegetation management programs and building regulations; however, little effort has been focused on the establishment of local land use policies to reduce wildfire damage to homes in the WUI. Land use policies influence the location and design of residential development, and can have a profound effect on exposure of those developments to natural disasters such as wildfire (Burby et al. 1999; Dombeck et al. 2004). A recent study found that the arrangement and location of residential structures strongly affects their susceptibility to being destroyed in a wildfire (Syphard et al. 2012). Land use planning tools that create patterns of growth to reduce wildfire vulnerability include:

1. Establish a buffer zone between residential properties and wildland areas (Fig. 2.1). The buffer zone could simply be a large area cleared of most vegetation, or could be designed open spaces. Many new developments are constructed around golf courses or recreational parks. However, placing these on the periphery could act as an important barrier to wildfire (Keeley et al. 2004).

2. Design subdivisions with clustered housing, rather than dispersed housing (Fig. 2.1). Land use planning that encourages compact development can reduce the loss of life and property during wildfire because there is less wildland vegetation and residences are easier to defend. Structure loss is more likely at low to medium housing densities, and where structures are surrounded by wildland vegetation (Syphard et al. 2012).
3. Prohibit/restrict development in very high wildfire risk areas. This includes preventing or restricting construction on slopes greater than 25%, in areas lacking reliable water sources, adequate roads, and containing highly flammable vegetation.

The goal of this study was to determine if state or local land use policies in California have been developed to protect new residential developments in the WUI against wildfire, and to what extent such policies have been implemented. This study characterized selected communities in the WUI to determine whether demographic or environmental conditions were related to implementing land use policies designed to reduce wildfire vulnerability. Specifically, this study looked at whether new residential developments in the WUI were clustered, had open space buffers, and/or were developed on slopes greater than 25%. Secondly, this study determined whether there was a relationship between elevation, housing density and/or previous experience with wildfire and presence of any of the land use tools. Lastly, land use policies at the state and county level were examined to determine if any focused specifically on decreasing the vulnerability of residential developments to wildfire.

Materials and Methods

A methodology was developed to select a subset of California counties in the WUI that have experienced increased housing growth, in terms of absolute numbers, between 2000 and 2010. First, counties were selected based on demographic, socioeconomic and locational characteristics. Next, census tracts within those counties were selected based on the level of wildfire threat and amount of housing growth. The final unit of analysis was the Census block group. Block groups are clusters of census blocks that generally contain between 600 and 3000 people. They are useful unit of analysis because they contain more detailed information than census tracts, and were created to permit the release of tabulated data that cannot be presented at the block level for confidentiality purposes. Block groups from each tract were selected based on level of wildfire threat and amount of housing growth. To determine whether state or land use policies pertaining to wildfire protection exist for the selected counties, state wildfire hazard and building codes as well as zoning ordinances and general plan elements for each county were acquired. To determine compliance with land use policies, Google Earth was used to visually interpret selected block groups. Lastly, geospatial data including digital elevation models (DEMs) and historical fire perimeters from CALFIRE were acquired to determine the relationship between physical gradients, fire history and presence of land use policies.

Selecting Counties

Five counties with distinct demographic and socioeconomic characteristics were selected for analysis in this study. These counties were distinct from each other but were each a part of a group of counties in the state with similar characteristics. The selected counties represented the unique characteristics of each group. This process started by identifying "communities at risk" for those cities and counties that are located in high risk fire zones, as defined by the California Department of Forestry and Fire Protection (CALFIRE). California contains 58 counties, 46 of which have more than two cities listed as "communities at risk". These counties are characterized by a wide range in socioeconomic status and environmental characteristics. Winkler et al. (2007)(Winkler et al. 2007) developed a typology for characterizing the demographic characteristics of the Inter-Mountain west reflecting the social and economic changes that have occurred in mountain regions over the past 30 years. Their analysis used census information such as migration information, education level, regional employment, change in housing units and housing value to identify four different types of communities: Classic Old West, Old West, New West and Model New West. This study used a similar approach to categorize counties in California, but included five groups rather than four used in the study. U.S. Census data from 2000 and 2010 were used to acquire information on (1) median household income; (2) college education; (3) percent vacant housing units for seasonal or recreational use; (4) percent population 65 years and older and (5) housing value. A statistical cluster analysis was used to group counties that were similar to each other.

One county from each group was selected. The final selection also included counties that represented geographic variability across the state.

Characterizing Housing Growth and Density

The process to characterize housing growth between 2000 and 2010 in each county required first acquiring GIS data of census tract boundaries for each county from the U.S. Census Tiger files. In addition, Fire Hazard Severity Zone (FHSZ) geospatial data were acquired from CALFIRE to identify the level of threat for each tract. Tracts were included if at least 50% of the 2010 tract was labeled high or very high. Once those tracts were identified for each county, census data were used to characterize the housing unit growth in each tract. Since tract boundaries have changed between 2000 and 2010, Brown University's Longitudinal Tract Data Base (LTDB) was used to bridge the two databases (Logan et.al 2012) so that the 2000 tract data matched the 2010 tract data. Housing unit data were acquired for each tract and the percent growth between 2000 and 2010 was calculated. For each county, the top one-third tracts with the greatest amount of housing unit growth were selected. The GIS block group boundaries within the selected tracts were then identified and overlaid with the FHSZ geospatial data. Block groups were included if at least 50% of the block group was labeled high or very high threat to wildfire. Lastly, census housing unit data for each block group was acquired for 2000 and 2010. Changing tract and block group boundaries required using the US Census Bureau block relationship files that enables the comparison of different geographies between the two years. Since the relationship files were available for census blocks and not block groups, it was necessary to group the blocks into block groups for each year, tabulate the total housing units for each block group in each year, and then match the 2000 data to the 2010 data. Block groups were eliminated from further analysis if the change in housing units between 2000 and 2010 was negative.

In addition to housing growth, the average housing density was calculated for each selected block group for 2010. Geospatial census data acquired from CALFIRE included habitable square miles for each 2010 census block. Habitable square miles excludes areas that cannot be developed like water and generally do not have residential development like federal lands. The habitable square miles for blocks were aggregated into block groups and then used with the 2010 housing unit data to calculate housing density for each block group.

Characterizing Residential Development

To determine whether housing development in block groups was clustered or not, block group boundaries were imported into Google Earth. The high resolution imagery enabled visual interpretation of determining where the new development occurred and whether it was clustered. Clustered and dispersed residential developments were easily distinguishable because typically, new residences in clustered developments were constructed in the cluster within a short period of time, generally one to three years, whereas dispersed residences were developed spatially further apart and sporadically across the entire 10 year period. Google Earth was also used to determine if new residential developments included open space buffers or cleared vegetation around the edge of the development. Lastly, geospatial data were used in a GIS to identify remaining characteristics such as elevation, slope and fire history. The average elevation and percent slope for each block group was derived from the DEM. The CALFIRE fire perimeter database was used to determine if the block groups had experienced fire anytime between 1990 and 2010.

Statistical analysis

A Generalized Linear Model (GLM) was used to determine if there was any statistical significance between elevation, housing density, previous fires and the presence or absence of land use planning tools pertaining to reducing wildfire vulnerability for all of the counties combined. GLMs, which are a type of logistic regression, enable the utilization of response variables that do not have normal distributions. In this study, the response variable was defined as the presence or absence of either clustered housing and/or buffers. If a block group contained at least one of these features, then it was given a 1, if not, then a 0. Two of the predictor variables, elevation and housing density were continuous variables, and the third predictor variable, fire history, was binary. If the block group experienced fire between 1990 and 2010, then it was given a 1, if not, then a 0. For each county individually, the mean elevation and housing density were compared with the presence or absence of clustering and buffering. Since San Diego County had a high number of block groups in the analysis, a simple linear model was used to determine the relationship between land use planning tools and elevation, housing density and previous fires.

Land use policies

To determine whether land use policies in any of the selected counties have been developed focusing specifically on reducing the vulnerability of residences to wildfire, both state and county level policy documents were analyzed. At the state level, regulations pertaining to development in high hazard fire areas are found in the Public Resource Code, the General Code and the Health and Safety Codes. At the county level, both zoning ordinances and elements of the General Plan were analyzed. Any specific policies or regulations pertaining to reducing wildfire vulnerability were categorized into 6 categories: Building materials (including roofing), accessibility, availability of water, vegetation management (individual), vegetation management (subdivision), and clustered development.

Results

Selecting Counties and Block Groups

The statistical cluster analysis resulted in five different groups of counties. This differed from the four groups identified by Winkler et al. (2007) because the fifth group, characterized by the highest income and housing values in the state was distinct enough from the other four groups. One county from each group was chosen for analysis (Table 2.1). The final five counties chosen, Humboldt (Group 1), El Dorado (Group 2), San Diego (Group 3), Santa Cruz (Group 4) and Marin (Group 5), not only represent a variety of demographic and socioeconomic conditions, but also represent different geographic regions of the state (Fig. 2.2). The Winkler et al. typology described Classic Old West and Old West communities as those with lower median household incomes, lower median value housing and a lower number of college-educated residents than New West and Model New West. Model New West communities were described as those located near high amenity destinations like ski resorts or large lakes. In this study, group 1 represented the lowest mean income, the lowest percent of college graduates, and the lowest mean housing value. These counties tended to be more rural and were similar to Winkler's Classic Old West or Old West communities. Group two had slightly higher mean income and college graduates than group 1, but the mean housing value was substantially higher, and the population greater than 65 years and seasonal housing was the highest of all five groups. This group was very similar to Winkler's New West or Model New West communities and included such counties as Mendocino, Alpine and El Dorado that have high recreational amenities, or are located in the fast-growing foothills of the Sierra. These counties also tend to be retirement destinations. Group 3 had higher mean income, higher college graduates, higher mean housing value and low seasonal housing. This group included counties with high amenities and expensive land prices, but is located closer to, or includes cities with high employment areas such as Sonoma, Alameda, Napa, San Diego and Santa Barbara. Group 4 and group 5, which contained a total of five counties, were very similar in some ways, but distinct enough to place them in two separate groups. All five counties are located in the San Francisco Bay area, with group 4 including San Francisco and Santa Cruz counties, and Group 5 including Marin, San Mateo and Santa Clara counties. While all 5 counties have high populations, expensive land prices and a variety of employment opportunities, the mean income of Marin, San Mateo and Santa Clara counties is significantly higher representing the high technology employment base in these areas.

The methodology developed to select block groups for each county resulted in a final count of 29 block groups for El Dorado county, 10 block groups for Humboldt County, 11 block groups for Marin County, 34 for San Diego County and 11 for Santa Cruz County. Each of the block groups were characterized as having high or very high threat to wildfire and had a positive increase in housing units between 2000 and 2010. The block groups were then characterized in terms of whether the new housing developments were clustered, had surrounding buffers, slopes greater than 25% and experienced fire (Table 2.2). The table indicates that San Diego County had the highest percentage of block groups that were clustered and had buffers. The highest percentage of block groups within San Diego County also experienced fire between 1990 and 2010. Block groups in Santa Cruz County had the lowest percentage of clustered development, while block groups in El Dorado, Marin and Santa Cruz had the lowest percentages of developments that had buffers. Marin and Humboldt counties had the highest percentage of block groups with slopes greater than 25% but this was primarily due to the block groups being very large in size. The actual development was often in one very small portion of the block group.

Statistical analysis

Results of the GLM analysis indicate there is a significant relationship between elevation and housing density and presence of clustering and/or buffers ($p < 0.05$), but no significant relationship between block groups previously experiencing fire and presence of clustering and/or buffers. The nature of the relationship between elevation and clustering and buffers was negative, meaning as elevation increases, the amount of clustering and buffering decreases. The relationship between housing density and clustering and buffers was positive, indicating as housing density increases, clustering and buffering increases. The GLM was used on data from all five counties combined, which resulted in no significant relationship between block groups experiencing fire and the presence of clustering/and or buffers. The simple linear regression for San Diego County resulted in a significant relationship ($p < 0.001$) between elevation and the presence of land use planning tools, but no significant relationship between housing density or fire. When comparing the counties to each other, residential developments at higher elevations were less likely to be clustered or have buffers (Fig. 2.3). Santa Cruz County was an exception to this, but difference in elevation between clustered and not clustered, and buffered and not buffered was very low. In general, residential developments were more likely to be clustered or have buffers at higher housing densities (Fig. 2.4). The exception was Marin County where sizes of the block groups were very large.

Land Use Policies

Prior to 1992, California's wildfire protection regulations for residential developments only pertained to jurisdictions located in State Responsibility Areas (SRAs). The state has primary responsibility for preventing and suppressing fires in these areas. Local or federal government agencies have primary fire protection responsibility in Local Responsibility Areas (LRAs). In 1992, California adopted the

Bates Bill (General Code Sec. 51175-51189), to extend wildfire protection regulations to LRA. At the state level, California has amended or enacted several pieces of legislation to require fire protection for new developments in the SRA and LRA. Any jurisdiction located in Very High Fire Hazard Severity Zones (VHFHSZ), as defined by CALFIRE, must adopt state fire safety standards, unless their standards exceed the state requirements. The primary state policy documents that specifically address wildfire protection are Public Resources Code (PRC) 4291, Title 14 of the California Code of Regulations (CCR), Chapter 7A of the California Building Code (CBC), and Chapter 47 of the California Fire Code (CFC). PRC 4291 requires 100 ft. vegetation clearance around structures in the VHFHSZ. Title 14 requires emergency vehicle access, private water supplies and vegetation modification. Title 14 also requires that proposed greenbelts in subdivisions must be placed between wildland fuels and structures. CBC Chapter 7A and CFC Chapter 47 require ignition-resistant building materials for new construction including roofs, exterior walls, decking and ancillary structures. Developments approved and constructed prior to 1992 do not need to meet these requirements. Local governments are required to implement these regulations through their building permit and subdivision approval processes for all developments proposed and constructed after 1992.

The Humboldt County General Plan contains information about wildfire protection in the Safety Element under the Fire Hazard section. This section specifically refers to County Code, Division 11 of Title III which includes wildfire mitigation strategies adopted from the state regulations. The Safety Element also discusses the county Master Fire Protection Plan (MFPP) which was developed to coordinate fire prevention and protection throughout the county. The MFPP was developed by the county's Fire Safe Council to prioritize areas for hazardous fuel reduction treatments and provide recommendations to mitigate these hazards. In addition to the state requirements, the county code requires new subdivisions to establish a County Service Area to provide maintenance of defensible space measures around developments. The Land Use Element of the General Plan briefly mentions that fire safety hazards in new developments will be implemented in accordance with state standards. It specifically mentions that fire breaks are required for hilltop development. The Land Use element also describes a Planned Rural Development Program Clustering Incentive Option, which is a voluntary incentive-based program to "minimize conflicts with timber harvesting and impacts to water resources, biological resources, wildland fire potential." (Humboldt General Plan Section 4.6.4, FR-S1). Limiting residential development on steep slopes (> 25%) is primarily found in the County Zoning regulations and addresses potential geologic hazards (landslides), not wildfire hazards.

Marin County's Countywide Plan includes policies that influence residential development in hazardous wildfire areas primarily in the Natural Systems and Agriculture Element. The Natural Systems and Agricultural Element policies include the removal of vegetation around structures, and prohibiting new land divisions in very high and high fire hazard areas unless adequate access, water, fire-resistant building materials and vegetation clearance is provided. As part of its Code of

Ordinances, the county has also implemented an Urban-Wildland Interface Code which enacts regulations from the state code regarding vegetation clearance, structural materials, vehicle access and water availability. Under subdivision design standards, the creation of parcels within a proposed subdivision is based on the slope of the parcel in relation to the area of the lot. For example, if the average slope of the lot is 40% or greater, the parcel must be a minimum of 1 acre in size. There are general slope standards for most areas in the county, but more restrictive standards in a few specific communities.

The Santa Cruz County General Plan addresses wildfire mitigation policies in two elements, the Safety and the Land Use Element. The Fire Hazards Objective (Objective 6.5) of the Safety Element addresses road accessibility, water availability and vegetation clearance. There is also a policy to locate building sites outside any designated Critical Fire Hazard Area (designated by the county), but if a building site cannot be located outside a Critical Fire Hazard Area, it must meet certain access criteria. This county has established a matrix system to determine the allowable residential density on lands designated Mountain, Rural, or Suburban Residential. The allowable density is based on site conditions listed in the Land Use Element. Of the nine factors of consideration listed, fire hazards are weighted more heavily than others such as landslides and seismic activity. Generally, higher density developments are permitted in areas that provide adequate accessibility and water. New development is not permitted on slopes exceeding 30% as specified in the

Geologic Hazards chapter of the county's Environmental and Resource Protection Code.

In addition to specifying policies on vegetation clearance, accessibility and water availability, the El Dorado County Public Health, Safety and Noise Element of the General Plan includes policies to limit development in areas of high and very high hazard as designated by the CALFIRE fire severity zone maps unless those developments submit a Fire Safe Plan that must be prepared by a Registered Professional Forester and approved by the local Fire Protection District and/or CALFIRE. Allowable land use densities are also dependent on the wildfire mitigation measures applied to the developments, and the element contains measures for implementation programs addressing the policies. For fire safety, the implementation program specifies working with local Fire Safe Councils, fire protection districts, the US Forest Service and CALFIRE to develop and implement a countywide Wildfire Safety Plan. The plan is supposed to include education and outreach activities, description and implementation of basic fire protection standards, fuel management standards, and standards for open space and greenbelts. This document was to be developed by the Planning Department, the Department of Transportation and the Building Department within six months of General Plan adoption. This Wildfire Safety plan was never adopted but instead the county implemented a Multi-Jurisdictional Hazard Mitigation Plan that included a Wildfire Protection Plan developed by the county Fire Safe Council. The plan addresses some the issues described in the General Plan but primarily focuses on education and outreach and implementation of fire safe practices for existing developments. The Land Use element of the General Plan "discourages" disturbance of slopes 30% or greater, but this is primarily to maintain the visual integrity of hillsides and ridgelines, not for safety purposes.

The Safety Element of the San Diego County General Plan specifies policies and action programs to address fire hazards. Policy 2 addresses considering site constraints in terms of fire hazards in land use decisions. The action program directs the County Fire Services Coordinator to classify the severity of fire hazard brushland areas and to specify the conditions under which development should occur. The Environmental Development Agency is directed to undertake a study to determine the adequacy of land division regulations as they relate to fire safety. The remaining policies discuss the coordination of fire safety efforts between agencies and organizations in the county, as well as adopting building and fire code ordinances. The Land Use Element has policies that specify the size of new parcels based on the slope of the lot. Generally, the steeper the slope, the larger the required lot size in all zoning districts. The Land Use Element also designates some land uses as "Environmentally Constrained" or "Impact Sensitive". The latter is applied to areas considered unsuitable for urban development for reasons of public safety or environmental sensitivity. The areas of public safety concerns are floodplains, faults and landslide potential with no mention of wildfire. The San Diego Fire Authority recently released the county Fire Master Plan, a five-year strategic planning document for policy makers. While the plan primarily focuses on fire prevention and coordination services, its Fire Prevention section addresses building code and defensible space requirements as required by the state.

Discussion

Land use tools such as clustering residential development, creating buffers between the development and wildland vegetation, and restricting building location can reduce the vulnerability of the development to wildfire. Although these tools could be incorporated into land use policies for new residential development, most policies related to preventing wildfire-related losses focus on building materials, road access, water availability and vegetation management for new development. California has enacted legislation requiring fire-safe building materials, adequate road access, adequate water availability and defensible space around all new development in VHFSZ, as defined by CALFIRE. All five counties in this study refer to these regulations within their General Plans and/or Building and Zoning Codes (Table 2.3). The building, access and water regulations are primarily enforced during the planning and building permitting and review process. However, although landscape plans are often required for determining compliance with the defensible space requirement, the ongoing maintenance is the responsibility of the individual homeowner resulting in sporadic enforcement of the regulation within and between counties. Although some of the counties considered housing density and slopes as factors for development approvals, only Humboldt County's voluntary clustering incentive option specifically addressed clustering for reducing vulnerability to natural hazards. Other counties required clustering alternatives for reasons other than wildfire. None of the counties completely restricted development on steep slopes, but allowed such development if sufficient mitigation measures were provided.

Although all counties had regulations requiring defensible space for new developments in high fire risk areas, visual interpretation of the fastest growing census blocks in each of the 5 counties indicated variation in compliance both within and between counties. Very few new residences in El Dorado, Marin or Santa Cruz counties had cleared vegetation, while San Diego residences had the highest percentage. Numerous studies have concluded that there is a resistance by homeowners in high fire risk areas to clear the vegetation around their homes for a number of reasons. In decades since World War II, the Sierra Nevada and other mountain regions have transformed from being a source of resource extraction to one of amenity attraction. In addition to these areas becoming valued destinations for retirement, income growth, increased corporate mobility, employment flexibility, and advances in communications technology have enabled people who used to be tied to an urban location to move to a more desirable exurban location, and still remain employed (Duane 1999; Theobald and Romme 2007; Travis 2007). People choose to live in high density vegetation but value the benefits of the environment over consideration of the risks (Daniel et al. 2002). People decide not to clear vegetation around their homes because it will decrease aesthetic value, or they underestimate the fire threat (Nelson et al. 2005). It is difficult for local or state government agencies to enforce the defensible space requirement because of diminishing resources; therefore many communities have turned to public education and outreach activities through their Fire Safe Councils. However, the findings in this study demonstrate the continued lack of compliance with that regulation.

The highest percentage compliance with the defensible space regulation was in San Diego County. This could be because the chaparral environment is less aesthetically desirable than a forest environment, and because San Diego County has experienced more devastating fires than other counties. There have been a number of studies focused on the positive public perception and scenic beauty of conifer forests (Brown and Daniel 1984; Han 2007). People who live in these forested environments may be less likely to want to clear the vegetation around their homes than those who live in a grassland or chaparral environment. Since San Diego County is primarily comprised of grasslands and chaparral, residents in these areas may be more likely to clear vegetation around their homes. In addition, San Diego County experienced devastating wildfires in 2003 and 2007, resulting in high structure loss. The results of this study show that 71% of the fastest-growing block groups have experienced wildfire in this county, increasing the likelihood of complying with the defensible space regulation. Although block groups in this county had the highest percentage of residential development with cleared vegetation, much of that cleared vegetation was around the outside of individual homes, not entire new subdivisions. In some cases, some new homes on the outside of subdivisions had cleared vegetation, but some had not, demonstrating that the burden of maintaining defensible space is on the individual homeowner.

With the exception of Humboldt County, clustered development was not considered for wildfire protection in any of the county general plans. It was encouraged in most counties for new subdivisions that could provide adequate road access and water. There was a significant relationship between the existence of clustered housing and elevation indicating that the lower the elevation, the higher likelihood of clustering. El Dorado and San Diego counties had the highest percentage of clustered developments, most located at lower elevations. Residential developments at lower elevations are typically closer to employment centers and therefore the demand for land may be higher resulting in higher housing prices. This results in land use zoning that allows higher density housing. In most counties, especially San Diego and El Dorado, as elevation increased, residential development became more dispersed. Higher elevations often contain greater vegetation cover, and residential developments in those areas may be more vulnerable to wildfire than those at lower elevations. For privacy and aesthetic reasons, people prefer to move to higher elevations for the increased vegetation cover, and decreased housing density. As a result, the likelihood of increased clustering at higher elevations is low.

Counties continue to permit development on slopes greater than 25% as long as mitigation measures are included. Both Humboldt and Marin counties had more than 80% of their block groups average greater than 25% slope; however, these block groups were very large and the residential development did not often occur in the steepest areas. Upon visual interpretation most counties were allowing development on ridges adjacent to very steep slopes. Wildfires usually travel uphill much faster than downhill, and the steeper the slope, the faster the speed of the fire. This makes development adjacent to steep slopes extremely vulnerable to wildfire.

Conclusion

Increasing population growth in high and very high hazard wildfire areas is resulting in unprecedented threats to human life and property across the Western United States. In California, large, high severity wildfires in the last 10 years have cost millions of dollars as fire management agencies protect threatened residences. Although many resources have been allocated towards pre-fire mitigation measures such as defensible space, building, access and water requirements, outreach and education efforts, very little has been focused on restricting the location and/or design of new residential housing. Recent studies have shown that the location and arrangement of structures strongly influences the vulnerability of those structures to wildfire (Syphard et al. 2012). In general, clustered housing developments are easier to defend than dispersed housing. Similarly, the likelihood of those developments to be destroyed by wildfire decreases significantly if they are surrounded by a buffer of cleared vegetation or some other designed open space. Lastly, since fires move quickly upslope, restricting development along or adjacent to steep slopes will also reduce wildfire vulnerability.

The focus of this study was to analyze land use policies and practices in five California counties to determine if any used land use tools to decrease the vulnerability of new residential developments to wildfire. All five counties have implemented the mandatory state defensible space, building and water access regulations through their general plans or other policy documents. San Diego County, although still continuing to allow development on steep slopes, utilized land use tools including clustering and buffering the most. Residents in this county had also experienced the greatest amount of destroyed structures due to wildfire in recent years, possibly resulting in a greater desire to prevent future disasters. This county is different than the other four because the high fire severity areas are located in highly flammable chaparral systems, as opposed to oak woodlands or conifer systems. People prefer to move to oak woodland or conifer systems because of the scenic beauty of the vegetation and are reluctant to modify their surroundings. Humboldt County had the only policy document that included a provision for clustered housing in rural areas to minimize conflicts with hazardous areas, including wildfire hazard, but that provision is voluntary.

Local land use agencies must develop and implement policies to decrease the vulnerability of homeowners and their homes, to wildfire. Although people move to these vulnerable areas for aesthetic and privacy reasons, they choose to ignore the level of threat to their lives and property. Policy makers and land use planners have been reluctant to implement policies that would impinge on these aesthetic and privacy issues. However, the losses are devastating when wildfires occur. More research needs to be conducted on the impacts of land use policies on reducing vulnerability to wildfire. Even San Diego County, which has been become a model for implementing land use policies addressing wildfire, needs to explicitly address these issues in their planning policy documents. Model regulations addressing defensible space building requirements have been developed. Now is the time to develop similar model regulations for restricting building density and placement in high fire risk zones.

Figure 2.1 Example of clustered development with a golf course buffer between the development and the wildland vegetation in San Diego County. Image courtesy of Google Earth.

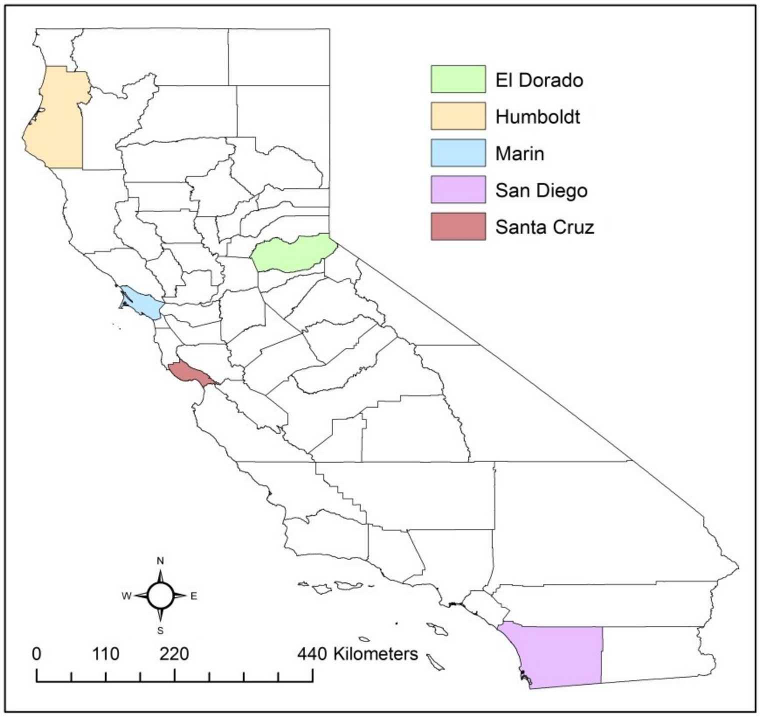

Figure 2.2 Counties selected for study in California

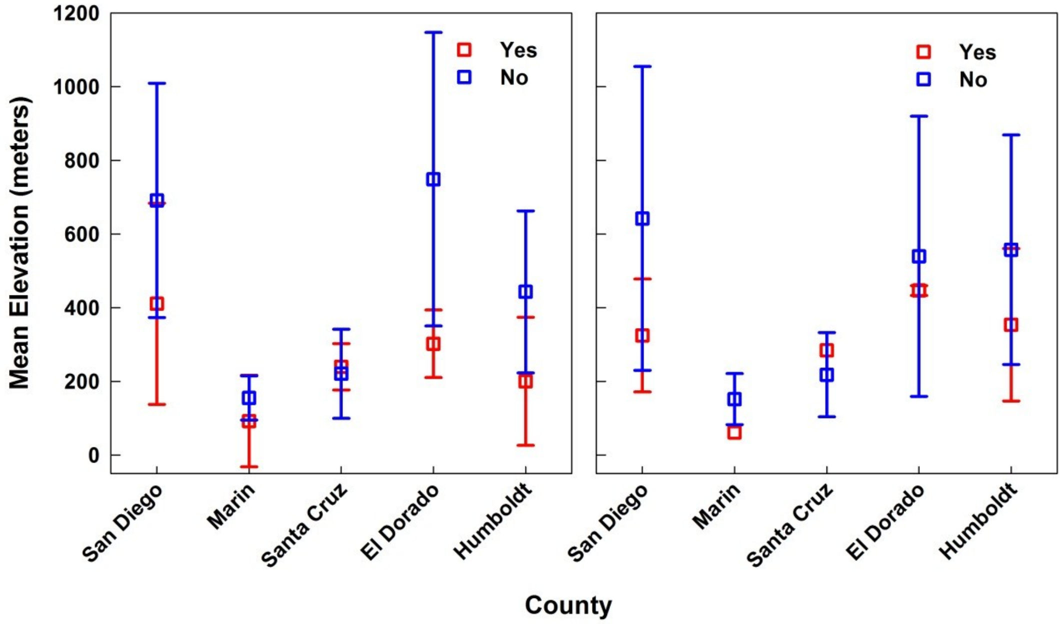

Figure 2.3 The comparison of the mean elevation for all selected block groups in each county with the presence (yes) or absence (no) of clustering (A) or buffers (B).

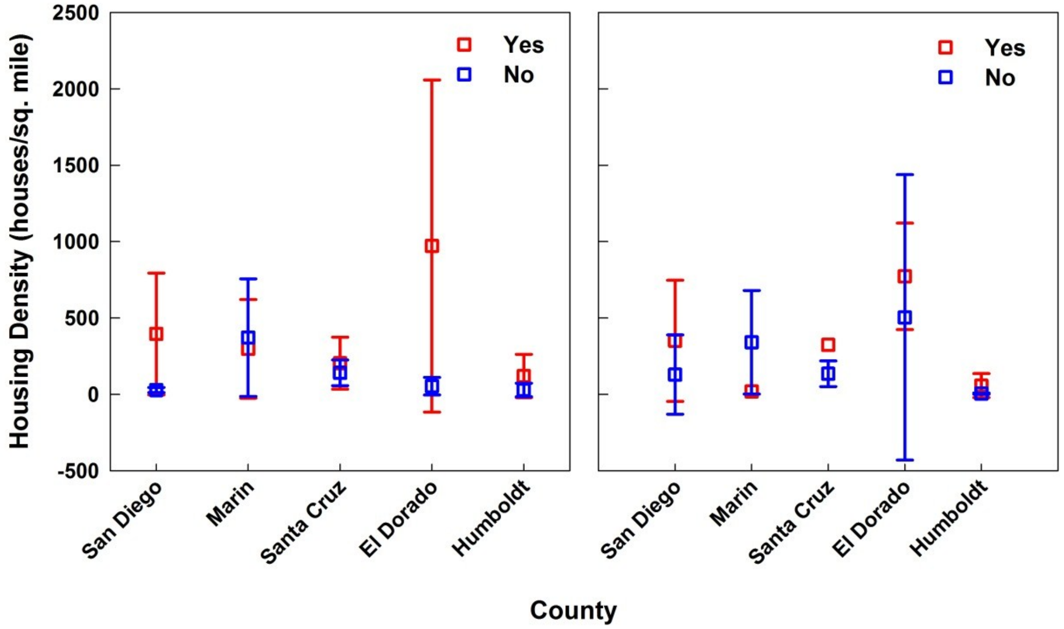

Figure 2.4 The comparison of the mean housing density for all selected block groups in each county with the presence (yes) or absence (no) of clustering (A) or buffers (B).

Table 2.1. Characterization of five groups of counties based on cluster analysis of 2010 Census data

	Mean Income	College (percent)	Mean housing value	GT 65 yrs (percent)	Seasonal Housing (percent)
Group 1	$33,199	23.2	$114,461	14.8	9.5
Group 2	$44,080	29.7	$177,008	16.1	15.3
Group 3	$52,035	36.8	$260,582	12.3	6.6
Group 4	$54,609	46.1	$386,950	12.3	3.4
Group 5	$72,153	50.5	$476,733	13.7	1.2

Table 2.2. Summary statistics for the percentage of block groups in each county that contained clustered development, buffers around developments, slopes > 25% or experienced wildfire.

	Clusters	**Buffers**	**Slopes > 25%**	**Experienced Fire**
Humboldt	20%	20%	80%	40%
Santa Cruz	18%	9%	45%	36%
Marin	27%	9%	82%	27%
El Dorado	48%	7%	31%	48%
San Diego	74%	76%	44%	71%

Table 2.3. Summary of land use policy documents pertaining to wildfire protection.

County	Land Use Policy Document	Vegetation clearance	Building requirements	Slope Restriction	Education Outreach	Building density
Humboldt	Safety Element	x	x			
	Land Use Element	x				x
	Master Fire Protection Plan (Fire Safe Council)	x	x		x	
	Zoning Regulations			x		
Marin	Natural Systems and Agriculture Element	x	x			
	Urban-Wildland Interface Code	x	x			
	Subdivision regulations			x		
Santa Cruz	Safety Element	x	x			
	Land Use Element			x		x
El Dorado	Public Health, Safety and Noise Element	x	x	x		x
	Wildfire Protection Plan (Fire Safe Council	x	x		x	
San Diego	Safety Element	x	x			
	Land Use Element			x		
	Fire Master Plan (San Diego County Fire Authority)	x	x			

CHAPTER 3

MODELING VEGETATION DISTRIBUTION AND ECOSYSTEM PRODUCTIVITY UNDER DIFFERENT CLIMATE CHANGE SCENARIOS FOR THE SIERRA NEVADA, CALIFORNIA

Introduction

Forest ecosystems play an important role in maintaining climate stability at the regional and global scales as a vital carbon sink. Changing climatic conditions are predicted to alter the distribution, composition and productivity of forest ecosystems globally. Increasing temperatures have lengthened the growing seasons (Xu et al. 2013) and improved forest productivity in mid-to high-latitudes (Schaphoff et al. 2006). However, decreased precipitation has increased tree mortality and reduced forest productivity in some drought-prone regions (Breshears et al. 2005). Rising temperatures are predicted to lead to species' migrations northward and higher in elevation, resulting in increased mortality in the more southern and lower elevation portions of species' distributions (Bakkenes et al. 2002). Climate-linked vegetation distribution shifts have been well documented in New Mexico (Allen and Breshears 1998), Nevada (Gworek et al. 2007), Vermont (Beckage et al. 2008), Spain (Penuelas and Boada 2003) and the European Alps (Cannone et al. 2007). In Southern California, dominant conifer species have shifted an average of 65 meters upslope over a 30 year period (Kelly and Goulden 2008). Given this evidence of changing vegetation distributions, it is critical that we try and understand the long-term implications of varying climate scenarios on forest ecosystems.

Two different approaches are generally used for assessing the impacts of climate change on organisms: niche-based species distribution models (SDM), or process-based models. SDMs assume that a potential species' distribution is mainly determined by climatic and environmental conditions (Gritti et al. 2013; Pearson and Dawson 2003). Process-based models such as the Dynamic Global Vegetation Models (DGVMs) project vegetation responses based on the interaction between vegetation dynamics and biogeochemical processes including the effects of CO_2 on production and water-use efficiency (Prentice et al. 2000). DGVMs characterize vegetation dynamics to increase the understanding of the relationship between global carbon sink and source dynamics, atmospheric CO_2 concentrations and climate change. While these models characterize global vegetation dynamics, they typically use spatially coarsely gridded climate data that are not accurate or useful for assessing regional or local effects of projected changes in climate (Cramer et al. 2001; Thrasher 2013). This is partially because regional precipitation patterns are not reliable using current climate models (Hulme et al. 1998), but also because the coarse grids do not capture the micro-climate of small areas, critical in understanding regional ecosystem dynamics. There is a need for higher spatial resolution climate datasets to model vegetation dynamics at a regional scale.

In this study, we used a DGVM, the Lund-Potsdam-Jena (LPJ) model (Sitch et al. 2003) to assess future vegetation dynamics and productivity under changing climate and atmospheric CO_2 concentrations in the Sierra Nevada in California. Downscaled climate projections (800 m) developed on the NASA Earth Exchange (NEX) scientific collaboration platform (Nemani et al. 2011) were used along with three different greenhouse gas emission scenarios. LPJ has been used to examine the sensitivity of biospheric responses to climate change for several global (Cramer et al. 2001; Schaphoff et al. 2006; Sitch et al. 2003) and continental scale studies (Gritti et al. 2013; Luo et al. 2008; Smith et al. 2001; Zaehle et al. 2007) but very few at the regional scale. The forests in the Sierra Nevada provide a unique opportunity to study vegetation dynamics and productivity across varied climatic conditions. Average air temperature increases and precipitation generally decreases along a latitudinal gradient from north to south. Although precipitation projections under different climate scenarios are varied in the Sierra Nevada, there is a consensus that temperature will increase across the entire region (Cayan et al. 2008). The Sierra Nevada provide numerous ecosystem services to California including timber, recreation, and is the primary source of water for the state (Duane 1999).

Methods

Study Area

The study area included the Sierra Nevada in California (Fig. 3.1). The Sierra Nevada is one of 10 bioregions in the state of California and is defined by specific physiographic features. The region is bounded on the west by the Central Valley, on the east by the Great Basin, on the north by the Cascades, and on the south by the Tehachapi Mountains and the Mojave Desert. The Sierra Nevada extends more than 640 km in a northwest-southeast trending axis along the eastern side of California, is approximately 110 km in width and encompasses ten National Forests and three

National Parks. Mountain peak elevations gradually increase from north to south. In the northern Sierra Nevada, peak elevations range from 1500 m to 2700 m. In the southern Sierra Nevada, the highest peak is Mount Whitney at 4421 m, the highest point in the contiguous United States. On the west side of the Sierra Nevada, forest types are dominated by *Pinus ponderosa* (Pinaceae) Lawson & C. Lawson (ponderosa pine) and *Pseudotsuga menziesii* (Pinaceae) (Mirb.) Franco (douglas fir), but also include *Pinus lambertiana* (Pinaceae) Douglas (sugar pine), *Calocedrus decurrens* (Cupressaceae) (Torr.) Florin (incense cedar) and *Abies concolor* (Pinaceae) Gordon & Glend. (white fir) at lower elevations and *Abies magnifica* (Pinaceae) A. Murray bis (red fir), *Pinus contorta* (Pinaceae) ex Loudon (lodgepole pine) and *Pinus jeffreyi* (Pinaceae) Balf. (jeffrey pine) at higher elevations. The drier east side consists of *Pinus edulis* (Pinaceae) Engelm. (piñon pine), *Pinus jeffreyi* and *Pinus ponderosa*. At higher elevations are *Pinus albicaulis* (Pinaceae) Engelm. (whitebark pine).

The climate in California is Mediterranean-type, with warm, dry summers and cool, wet winters with almost all precipitation falling between October and April. In the Sierra Nevada, average annual precipitation ranges from less than 51 cm in the south to over 200 cm in the north. Due to the Sierra Nevada rain shadow, precipitation is greater on the western side than the eastern side, and primarily falls as snow above 1500 m.

In recent decades California has experienced changing precipitation and temperature patterns. Both minimum and maximum temperatures have increased, with greater warming occurring in Southern California (Cordero et al. 2011). In the Sierra Nevada, minimum monthly temperatures have been increasing at the rate of 0.089°Cyr-1 between 1960 and 2000 (Thorne et al. 2008). Although no consistent trend in the overall amount of precipitation has been detected, a larger proportion of total precipitation is falling as rain instead of snow (Moser et al. 2008; Mote 2006; Vicuna and Dracup 2007). Current research envisions an overall increase in temperature of 2.5°C and 3% decrease in precipitation by 2060 for the Sierra Nevada (Pierce et al. 2013).

Climate and CO_2 Data

Historical (1950-2005) and projected (2006-2100) climate data were acquired from the NASA Earth Exchange Downscaled Climate Projections (NEX-DCP30) dataset. The NEX-DCP30 climate data are statistically downscaled to 800m from the Climate Model Assessment Program (CMIP 5) temperature and precipitation data using the Bias-Correction Spatial Disaggregation (BCSD) algorithm (Thrasher et al. 2013). The dataset includes 33 climate models and downscaled data under four Representative Concentration Pathways (RCP) greenhouse emission scenarios developed for the IPCC Fifth Assessment Report (AR5). This study used historical and future climate and CO_2 concentration data from RCP 4.5 and RCP 8.5 (Fig.3.2). The RPC 4.5 is a stabilization scenario and assumes that climate policies are invoked to achieve the goal of limiting emissions, concentrations and radiative forcing (Clarke et al. 2007). RCP 8.5, the highest emission scenario, is characterized by increasing greenhouse gas emissions reaching a maximum of 936 ppm by 2100 (Riahi et al.

2007). Climate projections for each RCP scenario for the Sierra Nevada are described in Table 3.1. Generally, mean maximum and minimum temperature changes increase and precipitation decreases from Northern to Southern Sierra. All changes in temperature in the Sierra are projected to be greater than California as a whole.

LPJ Model

LPJ (version 3.1.1) is a dynamic global vegetation model that combines plant biogeography with biogeochemistry to characterize vegetation dynamics and land-atmosphere carbon and water exchanges (Sitch et al. 2003). The model is of intermediate complexity and considers key ecosystem processes such as vegetation growth, mortality, carbon allocation and resource competition. Photosynthesis is simulated based on a simplified, semi-empirical version of the Farquhar model (Collatz et al. 1991; Haxeltine and Prentice 1996). The model assigns vegetation to ten Plant Functional Types (PFTs), which include bioclimatic limits to determine survival or regeneration under varying climatic conditions. This model differs from other DVGMs in that a grid cell can be occupied by more than one PFT. Each grid cell is divided into a fractional coverage of PFTs and bare ground, which compete locally for resources. More detail on this model can be found in Sitch et al. 2003.

The LPJ model was used to characterize annual vegetation dynamics and changes in Gross Primary Productivity (GPP) from 2010 to 2100. To attain model equilibrium, monthly climate data from 1950-1979 were used repeatedly to run the model from bare ground, with a spin up period of 1000 years. Initially, after the first spin-up run, the model was unable to reach equilibrium. In other words, the spin-up results indicated too much change in carbon pools and vegetation types between 1950 and 1979. The model was run for an additional 100 years using the results from the spin-up run, but randomizing the historical climate data (1979-1990) to eliminate any potential trends. The results from the spin-up runs were used to run the model from 1950 to 2010. Three future model scenarios were run for 2010-2100: (1) Climate from RCP 4.5 and constant atmospheric CO_2 concentration of 370 ppm; (2) Climate and CO_2 projections from RCP 4.5; and (3) Climate and CO_2 projections from RCP 8.5. The mean percent fractional coverage for each PFT was calculated for each scenario for the entire study region.

Results

Plant Functional Types

Although the model outputs ten PFTs, the Sierra Nevada does not contain any tropical vegetation or C4 grasses, so model results only include six of the ten: Temperate Needleleaved Evergreen (TNE), Temperate Broadleaved Evergreen (TBE), Temperate Broadleaved Summergreen (TBS), Boreal Needleaved Evergreen (BNE), Boreal Broadleaved Evergreen (BBE), and Grass (G). The LPJ model outputs the fractional coverage of each PFT per grid cell. Since more than one PFT can occupy a grid cell, then the areal extent of each PFT can total more than 100% of the study area. The overall spatial extent of each PFT for the initial year, 2010, is defined in Figure 3.3. C3 grasses occupy the entire study area, with TNE and TBS each occupying over 70% of the study area. TBE occupies the smallest area (21.3%).

Taking into account the fraction of the grid cell occupied by each PFT, mean fractional percent cover is greatest for C3 grasses, TNE and BNE and lowest for TBS and BBS (Fig. 3.4). Although TBS covers over 80% of the region, the mean percent fractional coverage per pixel is only 3%. Figures 3.5 and 3.6 shows the change in spatial extent and the change in mean percent fractional cover between 2010 and 2100 for each climate scenario. Overall, TNE shows no difference in spatial extent between the constant CO2 scenario and the RCP 4.5 scenario and only a small increase for the RCP 8.5 scenario. The mean percent fractional cover of TNE decreases for each scenario. After an initial expansion upslope and eastward, the amount of TNE decreases primarily in the higher elevations (Fig. 3.7). TBE shows no change in area between the Constant CO2 and RCP 4.5 scenarios but a large areal increase for the RCP 8.5 scenario. TBE show over 100% increase in mean percent fractional coverage for all three scenarios. The TBE PFT begins in the lower elevations on the western side of the Sierra Nevada and extends upslope an eastward as atmospheric CO2 increases (Fig. 3.8). Most of that increase occurs in the northern part of the region. BNE shows a small decline in spatial extent, but a large decline in cover. BNE primarily occurs in the higher elevations and on the eastern side of the Sierra Nevada. Fig. 3.9 shows the decline in percent fractional cover between 2010 and 2100 for the three scenarios. BBS show a decline in spatial extent but a small increase in cover. Lastly C3 grasses show little to no decline in spatial extent, but a sizeable decline in cover.

When comparing the different atmospheric CO_2 concentration scenarios, the spatial extent and plant cover for the constant CO_2 scenario and RCP 4.5 are very similar for most PFTs. The exception for this is the large increase in cover for TBS PFT between the constant CO_2 and RCP 4.5 scenario. Generally, the RCP 8.5 scenario results in a larger change in spatial extent and plant cover where there are increases in both for all scenarios. The exception is the smaller amount of plant cover of the TNE for both RCP 4.5 and RCP 8.5 compared to the constant CO_2 scenario. The RCP 8.5 scenario resulted in the greatest difference for the spatial extent of TBE and the plant cover of TBS PFT. Lastly, there was very little difference between the three scenarios for decreases in spatial extent or cover of BNS, BNE PFTs and C3 grasses.

Gross Primary Production

Overall, from 2010 to 2100 there is a projected 12.2 % increase in GPP for the constant CO_2 scenario, a 43.4% increase for the RCP 4.5 scenario and a 103.6% increase for the RCP 8.5 scenario (Fig. 10). Spatially, most of the increase of GPP is occurring on the higher elevation western slopes and eastern portions of the northern Sierra Nevada, along the higher elevations western slopes of the middle Sierra Nevada, and long the western slopes of the southern Sierra Nevada. Declines in GPP are projected to occur in the south eastern Sierra Nevada.

Discussion and Conclusion

The results of the LPJ DGVM for the Sierra Nevada generally agree with those using other DGVMs for California demonstrating the potential sensitivity of vegetation interactions with increases in temperature, atmospheric CO_2 concentration, and to some extent, precipitation, particularly in the northern Sierra Nevada (Hayhoe et al. 2004; Lenihan et al. 2008; Lenihan et al. 2003). Although vegetation characteristics of PFTs in the LPJ model are coarse, they can roughly be compared to the more detailed vegetation types described in other similar research. Lenihan et al. 2008 found reductions in the areal extent of Alpine/Subalpine Forest and the conversion of Conifer forest to Mixed Evergreen Forest attributed to increases in minimum temperatures. This corresponds with the decrease of the spatial extent and mean percent fractional cover of BNE and the large increase in mean fractional percent cover of the TBE as it moves upslope into the TNE under all three climate scenarios. The largest projected changes are the increase in areal extent and percent fractional cover of the TBE and the increase in percent cover by the TBS. However, the amount of TBS in the study area is small (3%), so this increase is not significant. Although the areal extent of grasses does not change between the different climate scenarios, the percent cover changes substantially (35-44%). This agrees with some reports of the reduction of high altitude meadows due to advancement of conifers (Harsch et al. 2009; Zald et al. 2012).

Actual observations of changing vegetation dynamics in the Sierra Nevada and other regions have been mixed. Increases in temperature and decreases in precipitation have resulted in increased mortality at the lower edges of species distributions in southern California, implying that some species may be moving upslope (Kelly and Goulden 2008). Whitebark pine, a high elevation conifer has recently experienced significant mortality due to beetle infestation, water deficits and increases in minimum temperature and ecosystem collapse is considered a possibility (Millar et al. 2012). Extensive high-elevation tree mortality has been observed in other regions in British Columbia (Carroll et al. 2004) and the Rocky Mountains and Colorado (Anderegg et al. 2013), suggesting widespread decline. Increases in hardwood densities at a hardwood-conifer ecotone have been documented in Vermont (Beckage et al. 2008). However, in a recent study of subalpine forest dynamics in the Sierra Nevada, the authors found that between 1934 and 2007 there has been no change in stand composition, although there has been an increase in the stem density of younger trees and a decrease in the stem density of larger trees (Dolanc et al. 2013). They speculate that vegetation in the Sierra Nevada may be experiencing a lag effect, and that we may see changes in the future.

The modeled GPP increases are primarily due to the increases in the areal extent and density of higher productive broadleaved PFTs, and the reduction of the needleleaved PFTs as well as the response of plants to higher atmospheric CO_2. The rate of GPP increase generally corresponds with the rate of atmospheric CO_2 increase for each climate scenario. Other studies have found similar results, with increases in productivity in mid-latitude and boreal regions due to increases in temperature and atmospheric CO_2 which stimulated plant biomass growth (Cramer et al. 2001; Lucht et al. 2006; Luo et al. 2008). This has resulted in the advancement of plant species in boreal regions, and increased “deciduousness” in mid-latitudes (Schaphoff et al. 2006). There is common acknowledgement in the uncertainty of the response to plants to additional atmospheric CO_2, as well as uncertainty in precipitation projections and their interactions with temperature projections. In some regions, productivity increased when temperature and precipitation increased; however productivity decreased when temperature increased and precipitation decreased causing drought conditions (Luo et al. 2008).

Vegetation in the Sierra is highly dependent on the interaction of precipitation and temperature. The recent decline in snowpack and the changes in timing of snowmelt in addition to increasing temperatures will increase drought stress of the vegetation, reducing the ability of the vegetation to resist pests and pathogens. LPJ, as with other DGVMs, projects the potential distribution of a Plant Functional Type based on bioclimatic limits and energy and water exchanges but does not consider other important factors such as dispersal abilities, complex biotic interactions or human activities, such as fire suppression (Gritti et al. 2013). LPJ also lacks the capacity to predict species-level responses, which may be important when considering processes such as fire, where fire sensitivity differs between species. However, because of the complicated nature of ecosystem responses to changes in climate, DGVMs provide important insight to how vegetation might behave in the future. The use of downscaled climate data improves the ability of the DGVM to assess future vegetation changes.   Forest ecosystems play an important role in maintaining climate stability at the regional and global scales as a vital carbon sink, so quantitative assessments of forest carbon (C) resulting from DGVMs are vital to both scientists and policy makers concerned with the implications of climate change.

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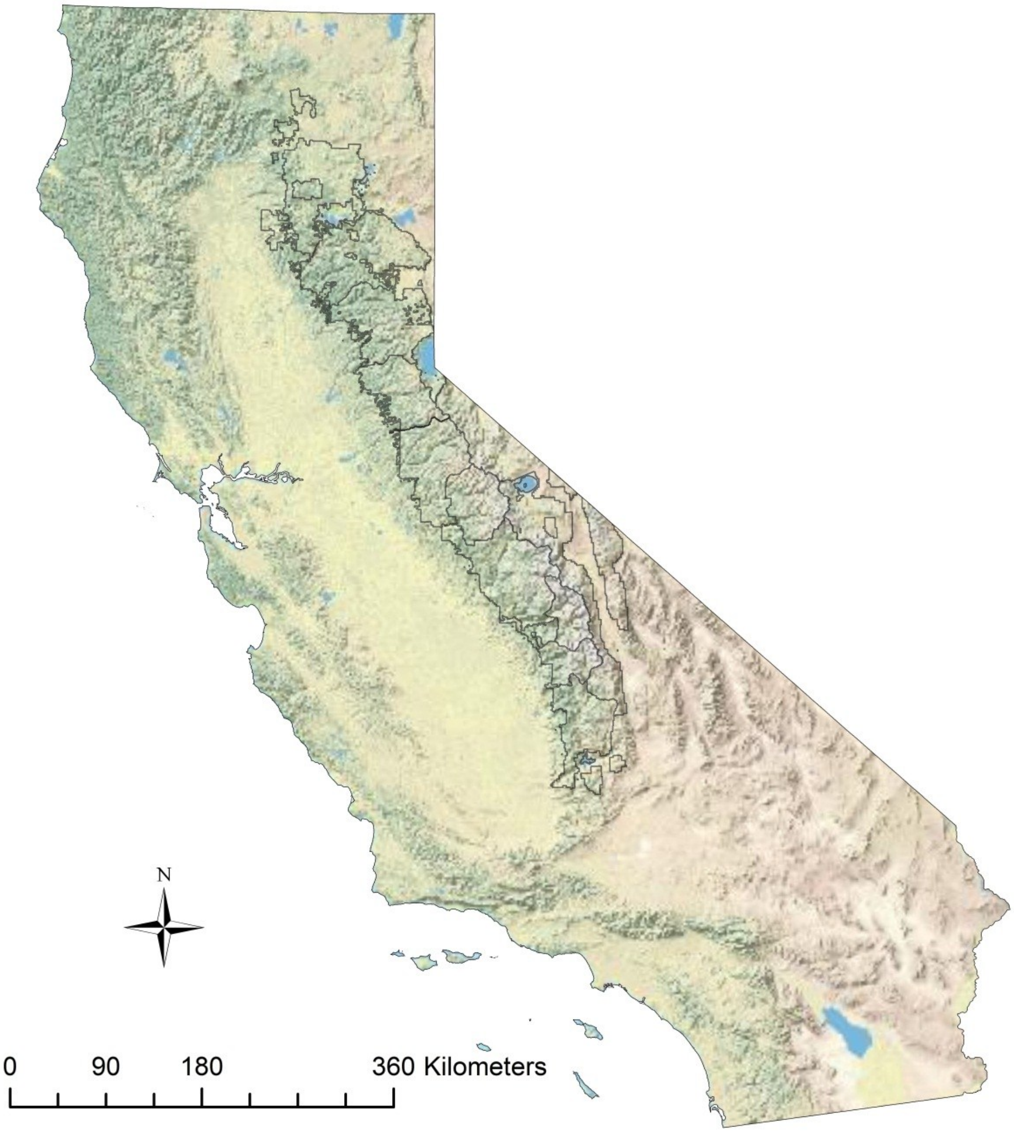

Figure 3.1. Study area within the Sierra Nevada. Included are the outlines of the nine National Forests and three National Parks included in the study

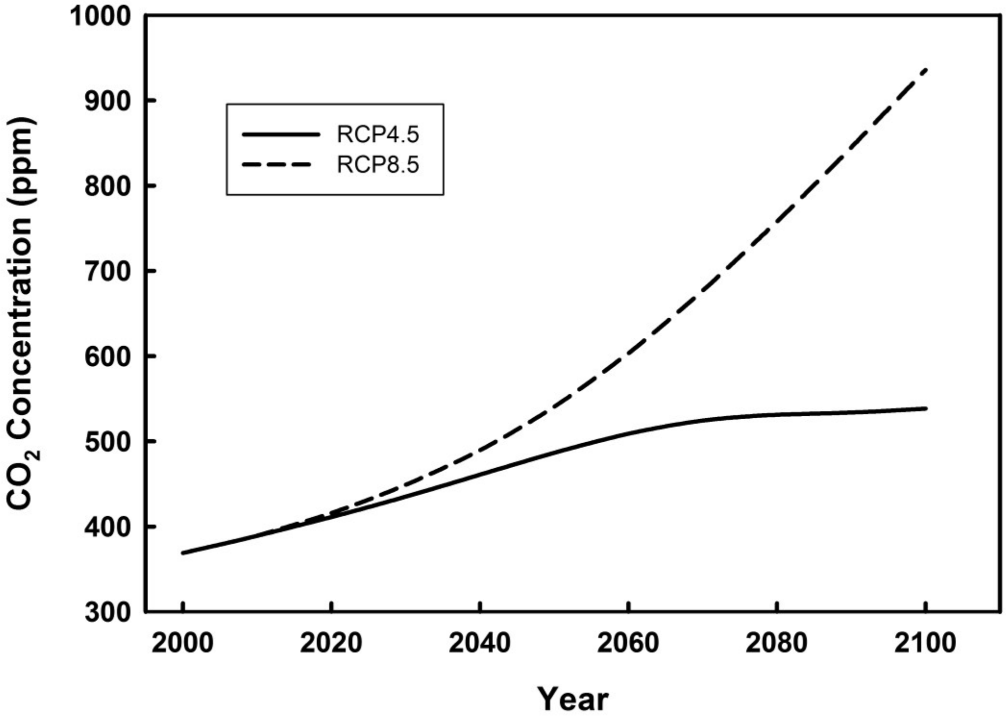

Figure 3.2. Projected atmospheric concentration of CO_2 for Representative Concentration Pathways (RCP) scenarios 4.5 and 8.5. Data acquired from the RCP Database (http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=about#intro)

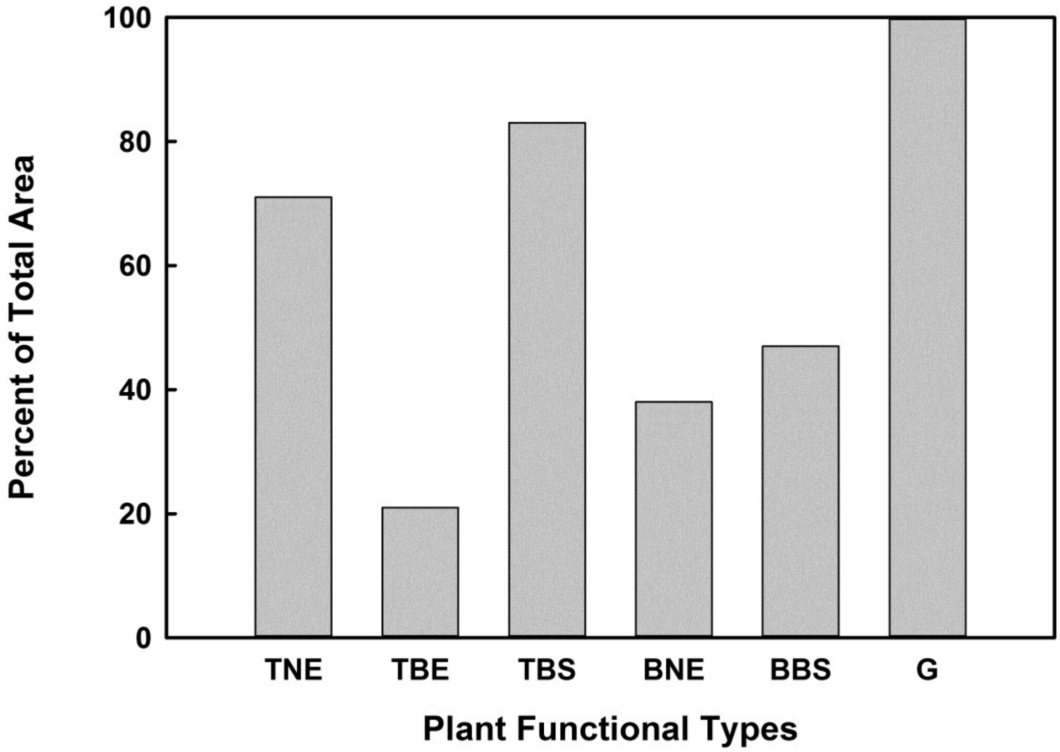

Figure 3.3. Percent of Total Area occupied by each Plant Functional Type (PFT). Each PFT can occupy a percentage of each grid cell, so the percentage of all the PFTs combined can be greater than 100%.

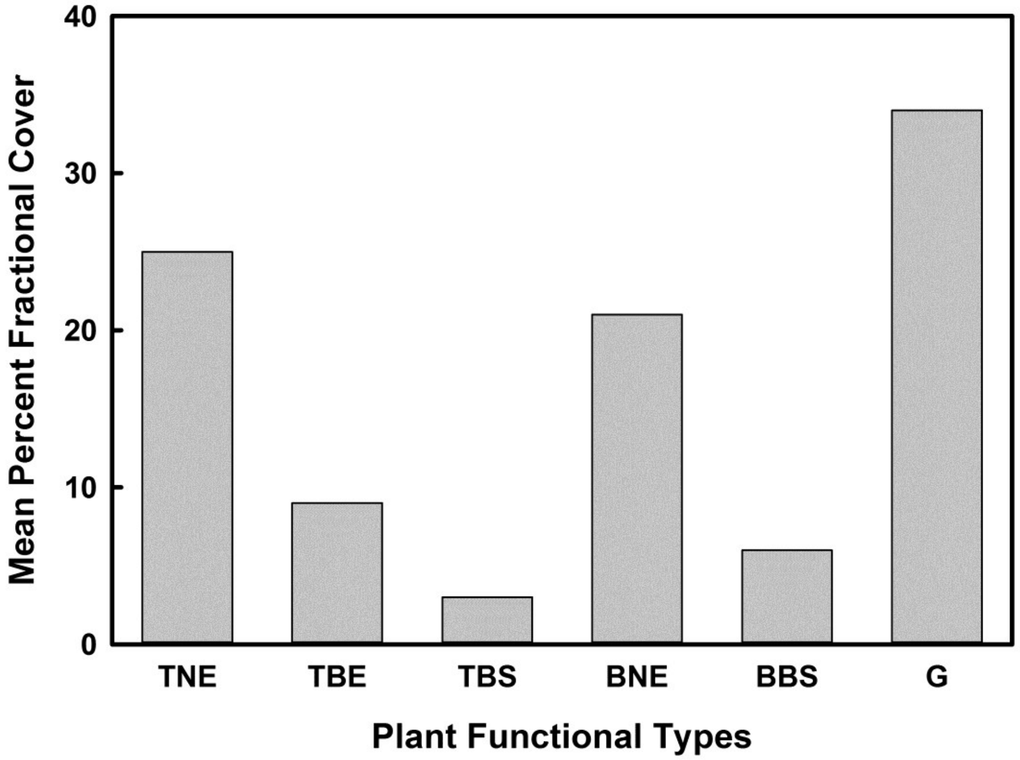

Figure 3.4. Mean percent fractional cover of each Plant Functional Type (PFT) for the entire region.

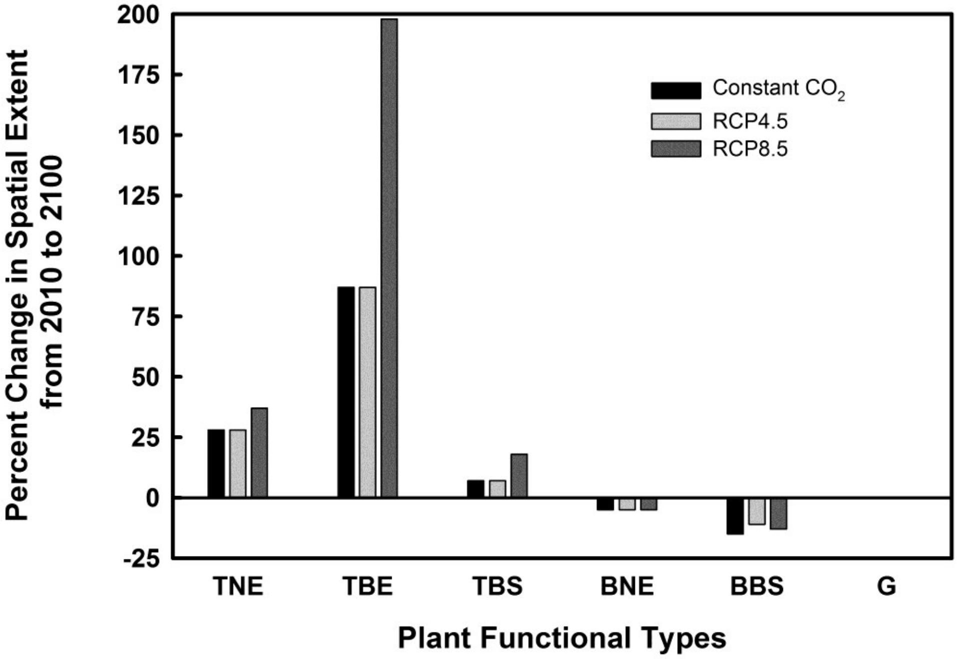

Figure 3.5. Percent change of spatial extent of each Plant Functional Type (PFT) for each climate scenario.

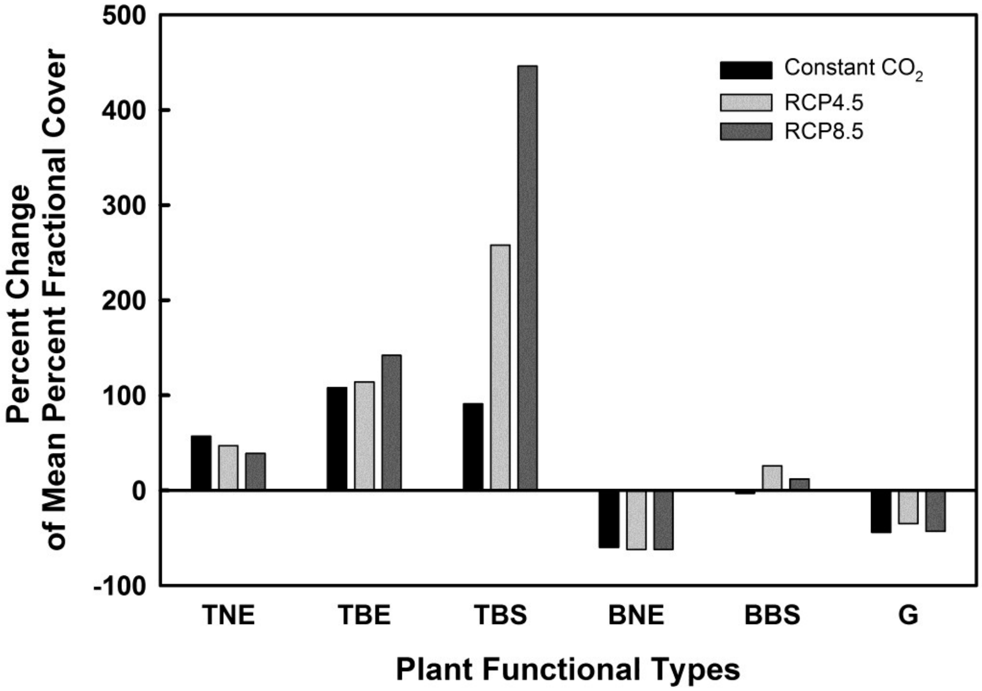

Figure 3.6. Percent change of mean percent fractional cover of each Plant Functional Type (PFT) for each climate scenario.

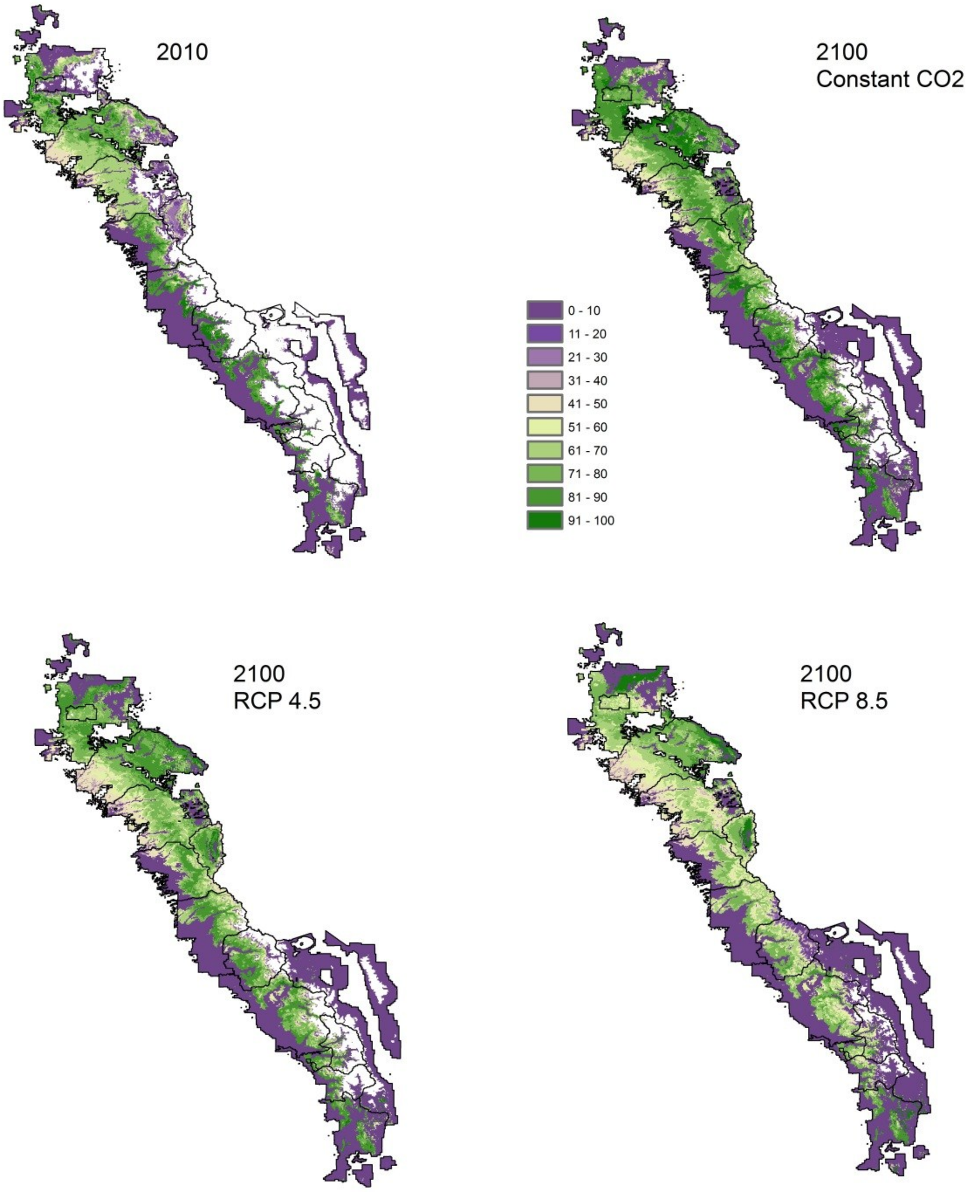

Figure 3.7. Percent fractional cover of Temperate Needleleaved Evergreen (TNE) between 2010 and 2100 for three climate scenarios.

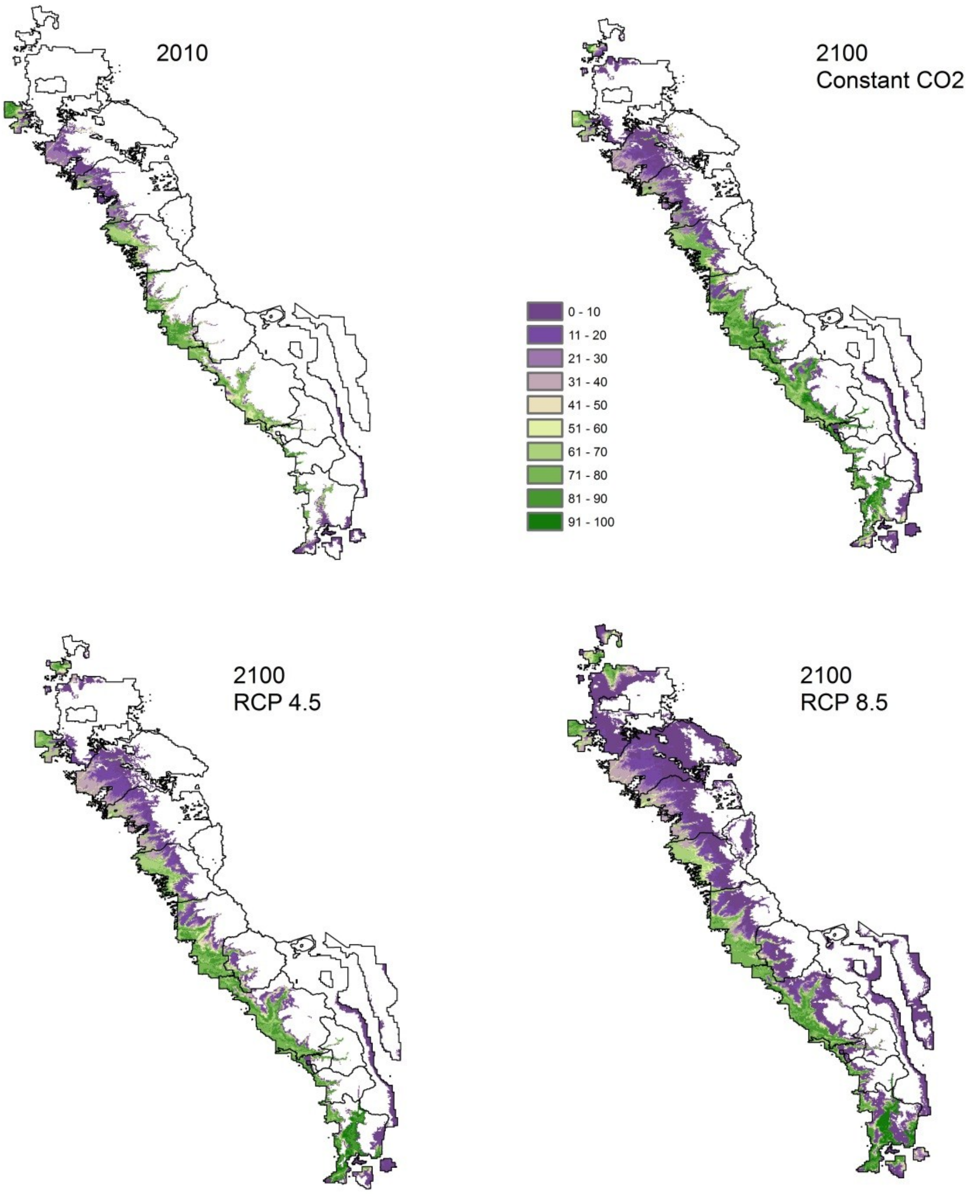

Figure 3.8. Percent fractional cover of Temperate Broadleaved Evergreen (TBE) between 2010 and 2100 for three climate scenarios.

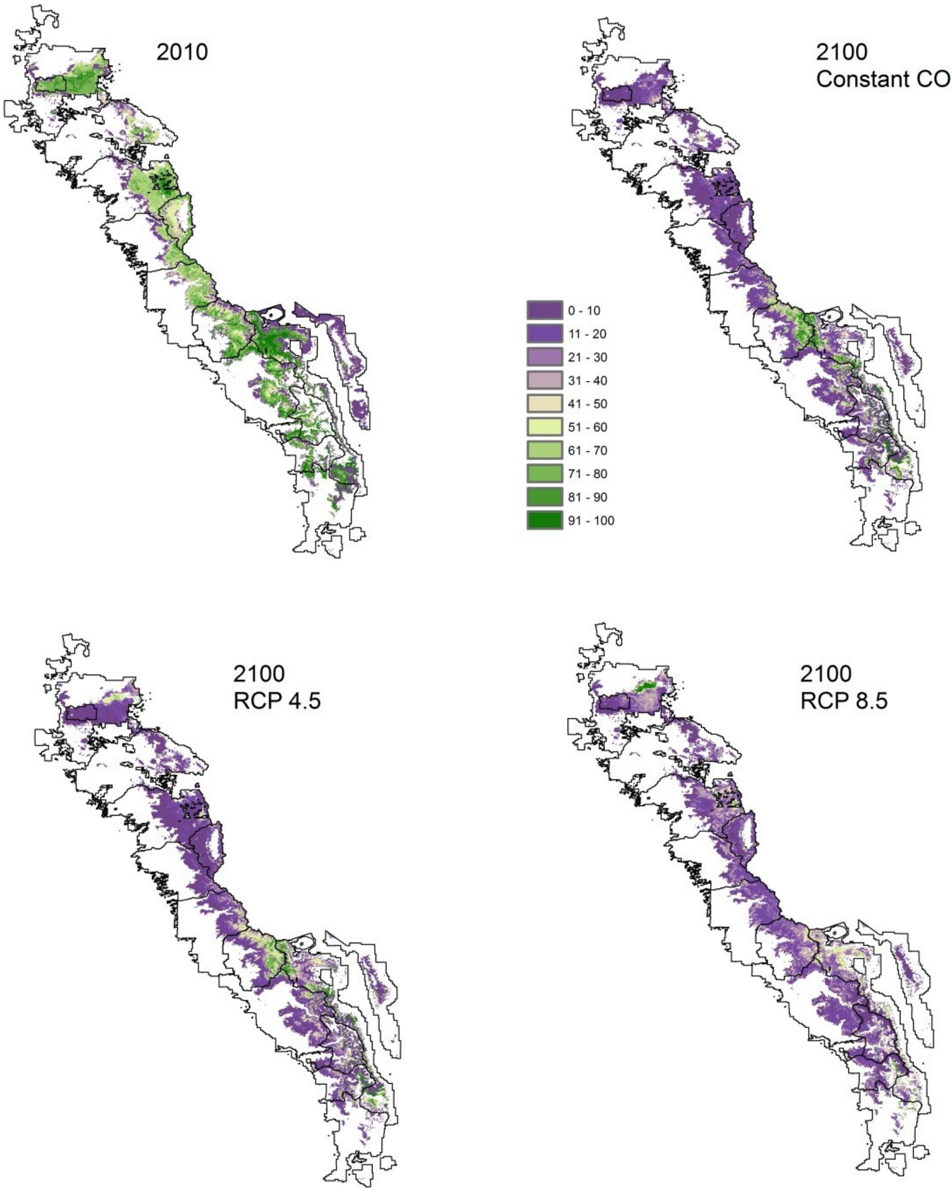

Figure 3.9. Percent fractional cover of Boreal Needleleaved Evergreen (BNE) between 2010 and 2100 for three climate scenarios.

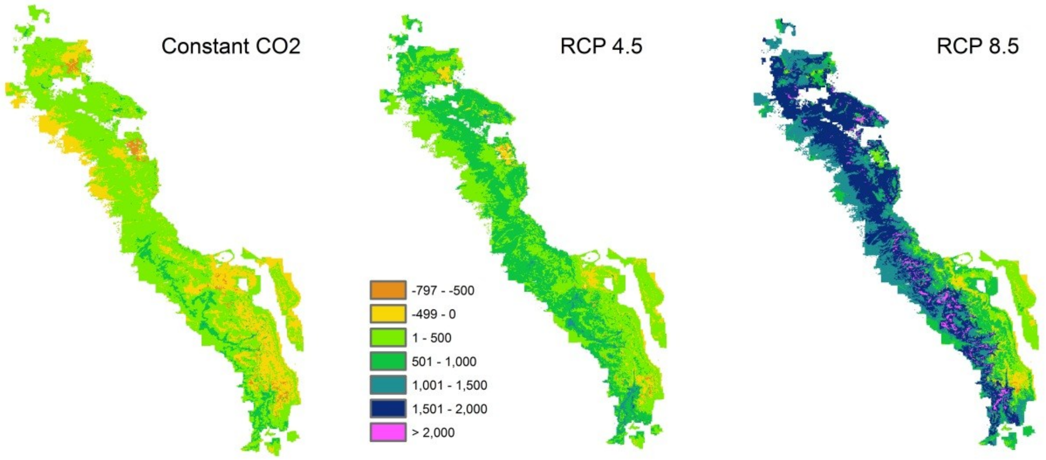

Figure 3.10. Difference in GPP (in gCm^{-2}y^{-1}) between 2010 and 2100 for three climate scenarios.

CONCLUSION

In this dissertation, I assessed the vulnerability of Sierra Nevada forests and their communities to current and future threats due to climate change and anthropogenic activities. I used an observational approach to assess past and current conditions and a modeling approach to forecast future conditions. In the following paragraphs, I summarize the results of each chapter and discuss the implications of these results on managing forest ecosystems.

Chapter 1 used Landsat satellite imagery to identify and attribute cause of forest disturbance, with a primary focus on mortality due to insect, disease and drought. Using Landtrendr, a change detection algorithm that uses annual Landsat time series imagery, I was able to successfully identify forest disturbance due to wildfire, forest management activities and insect, disease and drought. However, results also indicated that the program falsely identified many forest disturbances in areas of low tree cover. This is primarily due to the fact that the algorithm was developed for forests in the Pacific Northwest, an area of high density tree cover. There was also confusion in identifying the cause of disturbance due to insect, disease or drought and some management activities. In particular, thinning had very similar magnitude and duration characteristics to insect, disease or drought disturbances. In areas where management activities are abundant, such as the northern Sierra Nevada, this confusion was problematic.

The ability of multi-temporal satellite imagery to monitor annual and inter-annual disturbance will become crucial for forest managers to fully understand changing forest dynamics. It is critical to not only identify disturbance but to attribute cause to disturbance. The current algorithms, such as Landtrendr, can successfully identify disturbance but there are limitations in attributing cause. A ground observation network focused on monitoring forest disturbance does not currently exist, but could be extremely important in validating satellite observations. Similarly, improvement of the algorithm by adjusting its parameters by location to account for changes in vegetation type and cover, is needed. Lastly, development of accuracy assessment processes focused on multi-temporal data is important for forest managers to fully understand the usefulness of satellite-based disturbance products. Satellite imagery provides consistent, landscape-scale observations which will allow forest managers to better understand forest processes and manage carbon dynamics under future climate conditions.

Chapter 2 addressed the increasing vulnerability of human populations in high fire-prone regions by assessing land use policies and tools in selected counties in California. All five counties studied implemented the mandatory state defensible space, building and water access regulations through their general plans or other policy documents. San Diego County was the only county that regularly utilized additional land use tools including clustering and buffering around residential developments. This may be because residents in this county had also experienced the most severe wildfires, threatening more lives and destroying more structures than any other county.

Local land use agencies must develop and implement policies to decrease the vulnerability of homeowners, and their homes, to wildfire. The size and intensity of wildfires are projected to increase in the future, creating a greater need to protect valuable assets. Currently the primary burden of reducing vulnerability to wildfire is on the individual homeowner to clear vegetation around their homes. Research is beginning to emerge demonstrating the importance of design and placement considerations of new developments in high fire-prone regions. More research needs to be conducted on the impacts of land use policies on reducing vulnerability to wildfire, but there is reluctance by local officials with authority over land use planning and regulation to restrict the location and placement of new developments. This research has demonstrated that forests are changing, and land use planners need to understand the implications these changes will have on human populations.

Chapter 3 described the use of a DGVM to assess the impact of changing climate conditions on vegetation dynamics and productivity from 2010 to 2100. The most significant model results indicate that the mean percent fractional cover of Temperate Needleleaved Evergreen plant functional types will decrease, primarily at higher elevations (above 1800 m). Temperate Broadleaved Evergreen plant functional types increase in spatial extent and percent fractional coverage by moving upslope and eastward as atmospheric CO2 increased. Boreal Needleleaved Evergreen plant functional types, which now primarily occur in the higher elevations and on the eastern side of the Sierra Nevada, showed a small decline in spatial extent but a large decline in percent fractional cover. This change is currently being observed with the high mortality of Whitebark pine on the eastern side of the Sierra Nevada. There was a projected increase in GPP for all three scenarios, the greatest increase occurring with the highest CO2 concentration. This is primarily due to increases in the spatial extent and increased density of the more productive broadleaved plant functional types.

Results of this modeling effort will be valuable in managing forests for the future. Certainly, DGVMs have limitations which must be considered when analyzing results. Generally, DGVMs do not consider important factors such as plant dispersal abilities, complex biotic interactions or human activities. This model also lacks the capacity to predict species-level responses, which may be important when considering processes such as fire, and restoration activities. It is also important to continue to collect ground information to refine and assess the accuracy of models. Most importantly, it will be important to incorporate disturbance dynamics (Chapter 1) and human population growth (Chapter 2) into the models. Changing disturbance dynamics in the form of increased wildfires and increased tree mortality due to drought and insects may result in decreased productivity. Forest managers will need to understand the balance between trees and disturbance moving across the landscape driven by a changing climate. Currently these two processes are measured independently, but must be integrated in the DGVMS of the future.

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