THE IMPACT OF CLIMATE CHANGE ON CALIFORNIA TIMBERLANDS

A Paper From:
California Climate Change Center

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FINAL PAPER

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Arnold Schwarzenegger, *Governor*

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts focus on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's PIER Program established the **California Climate Change Center** to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The California Climate Change Center Report Series details ongoing center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the center seeks to inform the public and expand dissemination of climate change information, thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

California timber production has been declining in an era of warming, increased wildfires, land use change, and growing emphasis on recreation. Climate change has the potential to further affect the California timber production and prices. The direction and magnitude of change will depend on individual site characteristics and projected climate change. Examples of potential climate change effects include changes in individual tree growth rates, forest dieback, and shifts in species ranges and ecosystem composition. When coupled with changes in global timber prices, which themselves are the result of productivity changes, this leads to important consequences to California's private timberlands. The ecological responses to climate change are dynamic and these complexities should be considered when predicting future timber production in California. Past attempts have modeled climate change impacts on the timber industry in California but did not consider dynamic land-use change or biologically relevant spatial resolution. This study uses models that project tree species productivity and movement across the landscape under climate change, coupled with economic models of landowner adaptation and returns from multiple harvest strategies. Our results show that under likely price scenarios, climate change will result in an overall decline in the value of harvested timber in the state, with decreases of 4.9 percent to 8.5 percent by the end of the century, depending on climate change scenario, price scenario and management option, with dollar losses totaling up to $8.1 billion. There is great spatial variation within these statewide averages. Many areas of the state show substantial declines in timber value, while a smaller number of areas show modest increases in value, under price scenarios that reflect the impact of climate change. If prices are not affected by climate change, more areas experience gains in value. Management options influence the degree of loss, indicating that programs fostering adaptation to climate change may pay important economic benefits. Declining timber value corresponds disproportionately to areas already experiencing conversion of timberlands to housing or agriculture. Policy measures to stem conversion of timberlands due to climate change may warrant consideration.

Keywords: California, timber, climate change, carbon credit, growth rate

Executive Summary

Introduction

California timber production has been declining in an era of warming, increased wildfires, growing emphasis on recreation, and threatened species protection. Production fell 27 percent from 1991 to 1996 and declined another 24 percent in the subsequent decade. Decrease in sales from federal lands, driven by heightened emphasis on recreational use and protection of threatened species, has been the largest contributing factor. By the mid-1990s federal timber sales were at 50 percent of their levels in the previous decade.

Climate change has the potential to further change California timber production. Warming may promote growth, while drier conditions or earlier snowmelt may reduce growth and harvest potential. The direction and magnitude of change will depend on individual site characteristics and projected climate change. The impact of climate change will also depend on climate change influences on the timber market. If growth of northern softwood forests increases with warming, timber prices may fall, further affecting California’s timber producers.

The combined effects of climate change, a declining timber industry, and booming land values may drive major changes in timberland land use. Timber production must compete with expanding ex-urban housing and demand for land for second homes, as well as in some areas with vineyard expansion. The Mendocino coast for example, has seen wine production surpass timber as the top source of revenue in the county. The interplay of climate change, declining production and land use demands therefore has the potential to dramatically alter California landscapes. This study explores the economic impact of climate change on value of timberlands and the possible implications for these changes on land use.

Purpose

The future of California's timberlands has important implications for the economy of the state and the evolution of land use patterns. This study’s purpose is to advance understanding of climate change effects on these values.

Project Outcomes

Our results show that climate change will result in an overall decline in the value of harvested timber in the state, with decreases of 4.9 percent–8.5 percent, depending on climate change scenario and management option under climate change price assumptions, and slight gains if climate change has no effect on prices. Dollar losses amount to up to $8.1 billion (non-discounted) by 2080 in scenarios in which prices respond to climate change in ways that have been predicted in the literature. Dollar losses are always negative and always above one billion dollars by 2080 in these price scenarios. Where international prices do not respond to climate change (considered unlikely), dollar gains are always positive and range from $1.4–$5.4 billion by 2080.

There is substantial spatial variation within these statewide averages. Many areas of the state show substantial declines in timber value, some arising almost purely as a result of falling reduced global timber prices, and some arising from decreases in productivity. A smaller number of areas modestly increase in value as a result of climate change under climate change price assumptions, and a larger number of areas increase in value if climate change is assumed not to influence prices.

Management options influence the degree of loss, indicating that programs fostering adaptation to climate change may pay important economic benefits. Prices for timber are expected to vary with climate change, an important component in driving down values in California. Many areas experience severe declines in value even under base case (no climate change influence on price) scenarios, however. Carbon payments may help reduce some of the most severe declines, but do not change the spatial imbalances between locations hardest and least impacted. Declining timber value corresponds disproportionately to areas already experiencing conversion of timberlands to housing or agriculture.

Conclusion/Recommendations

Climate change results in a net negative impact on timber value in the state of 4.9 percent–8.5 percent under likely price scenarios. Impacts vary greatly between and within counties. Training to help managers cope with climate change (adaptation training) can help reduce impacts in the hardest hit areas, as can payments from carbon markets. Climate change will increase pressures to convert timberlands to other land uses. Forest benefits and ecosystem services not well captured in markets, such as watershed protection, recreation and nature conservation, may be lost as declining timber value and increasing urban pressures converge. Policy measures to stem loss of timberlands due to climate change may warrant consideration.

1.0 Introduction

1.1. Timber Industry in California

California timber production has been declining in an era of warming, increased wildfires, growing emphasis on recreation, and threatened species protection. Production fell 27% from 1991 to 1996 and declined another 24% in the subsequent decade. Decrease in sales from federal lands, driven by heightened emphasis on recreational use and protection of threatened species, has been the largest contributing factor. By the mid-1990s federal timber sales were at 50% of their levels in the previous decade. From 1996 to 2005, the total timber production in California decreased from 2,272,928 thousands of board feet to 1,725, 024 thousands of board feet (Figure 1.1.1).

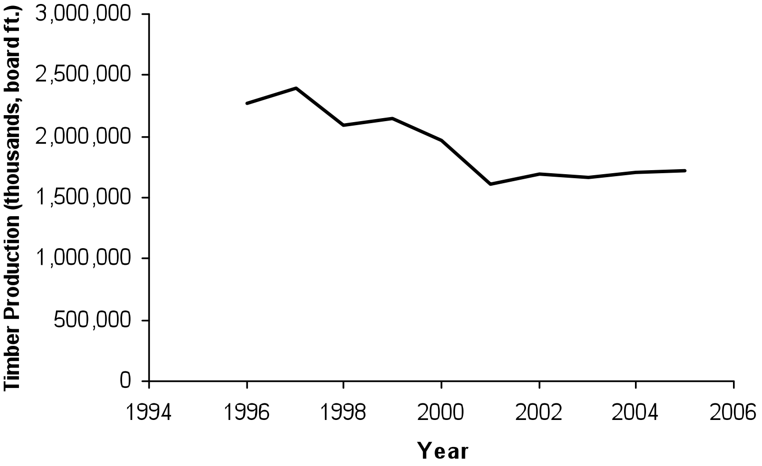

Figure 1.1.1. Total timber production (thousands of board feet) for California between 1996 and 2005

Adapted from State Board of Equalization, Research and Statistics Section (Spero 2006).

1.2. Climate Change and Timber

Climate change has the potential to further change California timber production. Warming may promote growth, while drier conditions or earlier snowmelt may reduce growth and harvest potential. The direction and magnitude of change will depend on individual site characteristics and projected climate change. The impact of climate change will also depend on climate change influences on the timber market. If growth of northern softwood forests increases with warming, timber prices may fall, further depressing California production.

The combined effects of climate change, a declining timber industry, and booming land values may drive major changes in timberland land use. Timber production must compete with expanding ex-urban housing and demand for land for second homes, as well as in some areas with a boom in vineyard expansion. The Mendocino coast for example, has seen wine production surpass timber as the top source of revenue in the county. The interplay of climate change, declining production, and land use demands therefore has the potential to dramatically alter California landscapes. This interaction of climate change and market forces is the focus of this study.

Timberland is defined as land "…administratively available for timber management and where growth potential exceeds 20 cubic feet per acre per year" (FRAP 2003 Assessment). There are 16.7 million acres of designated timberlands across California, although these areas are often considered not "suitable" for production due to current management regimes or ownership constraints. Of the total timberlands in California, 9.2 million acres are publicly owned. The major timberland areas defined by the Forest Inventory and Analysis (FIA) program are Central Coast, North Coast, North Interior, Sacramento, and San Joaquin / Southern—all of which are comprised of both private and publicly owned land. These regions cover various ecosystem types that contribute to the timber industry according to their species composition.

Climate change over the next several decades is predicted to have major impacts on vegetation in California. Those ecosystems that host vegetation to contribute to the timber industry in California are no exception. Examples of potential climate change affects include changes in individual tree growth rates, forest dieback (van Mantgem and Stephenson 2007), shifts in species ranges, and ecosystem composition. The ecological responses to climate change are therefore dynamic and should be considered as such when predicting future timber production in California.

Previous studies have incorporated dynamic ecological models with global economic models. They predict global increases in timber production resulting in decreased timber prices (e.g., Sohngen et al. 2001). However, general patterns seen at the global scale do not necessarily reflect those projections at the state level. For California, a state that hosts heterogeneous landscapes and microclimates, these general patterns cannot be applied. Mendelsohn (2006) modeled climate change impacts on the timber industry in California but did not consider species' dynamics or biologically relevant spatial resolution. It is necessary to use more specific models that incorporate downscaled GCM (General Circulation Model) data that predict species movement across the landscape with species-specific growth parameters to model stochastic optimization strategies for landowners.

We assume that harvest from federal lands will continue to decline and be heavily regulated, largely insulating this harvest from market forces. We therefore restrict our analysis to privately held timberlands. There is little reason to think that impacts on federal lands would be significantly less than those we calculate for private lands.

1.3. Role of this Study

This study builds on previous efforts by emphasizing land values and by incorporating dynamics in species distributions, productivity, and land manager behavior. It links two types of biological models with economic optimization models. Biological models provide estimates of changes in productivity and species' ranges due to climate change. The economic model incorporates land manager behavior in three management options: (1) naïve to climate change, (2) able to adjust rotation intervals to optimize with respect to climate change, and (3) able to adjust both rotation and species mix in response to climate change. This approach gives a more robust notion of the changes in timberland value that may result from climate change dynamics, as well as providing insights into policy levers (such as promoting awareness of climate change) that may influence land manager behavior and reduce damages due to climate change.

1.4. Project Objectives

The goal of this project was to assess climate change impacts on California's timberlands. This goal was pursued through three main objectives:

- Determine the cost of climate change based on future scenarios of growth and distribution of tree species
- Explore the economic implications of various timber management strategies in the face of climate change
- Preliminary assessment of the effect of carbon markets on changes in value of timberlands

1.5. Organization

The remainder of the paper is divided into three main sections. Section 2 describes the methods used in both the biological and economic models, as well as the assumptions underlying the study. Section 3 presents the results, both in aggregate and in several spatially explicit formats. Section 4 provides a synthesis of the two modeling chapters and recommends future steps for California's timber industry in the face of climate change.

2.0 Methods

In this section we outline the methods for mapping climate change scenarios into productivity changes, into silvicultural practices, and ultimately into economic impacts.

2.1. Introduction

Our modeling approach couples models of ecological productivity, landowner (forester) behavior, optimization, and economic value to estimate the consequences of climate change on California's private timberlands. Climate change affects tree growth and distribution. Landowners respond in various ways to dynamical shifts in productivity, giving rise to economic impacts. We assess the impact of carbon pricing by adding a model that gives value to carbon stored in forests. This model does not simulate market forces (we use a fixed price for carbon) but allows a generic assessment of how significant carbon pricing may be for altering land management options such as timber rotation cycles. In contrast, we do assume changing prices for timber, based on values in the literature.

Our models provide a more sophisticated and broadly integrated assessment of climate change impacts than previous assessments have allowed. However, there are many complexities of biology, markets, and industry that have had to be omitted to obtain this overview. Specifically, alternative uses of forest biomass, such as chipping for fuel, have been omitted. We do not model the biological effects of larges scale disturbances such as fire or insect attack. And we are unable to simulate advances in the industry that might increase value per unit of land area or respond to new markets.

We anticipate that productivity in some regions could increase and that it will decrease in other areas. Landowner behavior may mitigate negative impacts, which will be a focus of our analysis. Carbon valuation may alter the value trends suggested by biological and market forces. We begin with a description of the ecological productivity models and then turn to the integrative economic models.

2.2. Ecological Models

2.2.1. Model Description

The goal of the productivity modeling is to predict the effects of climate change on the growth rates of timber species throughout California. To predict growth, the model requires information on soil conditions (which vary by location), climate conditions (which vary by location as well as over time), and species-specific physiological parameters. The model produces time series of wood volume for each timber species that may grow at a given site, and these volume outputs are used as inputs to the economic model for the valuation analysis.

Growth rates are predicted using a simplified physiological process model, 3-PG (Physiological Principles for Predicting Growth). Landsberg and Waring (1997) developed 3-PG in an effort to make forest process models, which typically require detailed physiological measurements in order to successfully predict growth; more useful in a forestry management context, where such detailed data are seldom available. Because it uses readily available input data and few parameters, it has successfully been used to predict growth in a wide variety of settings (Landsberg et al. 2002). It has been used in several timber-related studies in Oregon (e.g., Coops and Waring 2001; Swenson et al. 2005), but this study will be the first large-scale application of the model in California.

The 3-PG model uses species physiological characteristics to model growth in single-species, even-aged stands. Monthly climate data—consisting of maximum temperature, minimum temperature, precipitation, and solar radiation—drive the simulation. The model uses these factors to calculate rates of carbon fixation from photosynthesis (i.e., net primary production) and partitions the resulting biomass to foliage, stems, and roots according to species-specific allometric ratios. A simplified hydrologic model tracks available soil moisture on a monthly time step, limiting the efficiency of photosynthesis during periods of drought. Nutrient limitation is also incorporated via a fertility rank parameter. Low fertility values inhibit photosynthesis and cause a greater proportion of biomass to be allocated to roots. Finally, as the stand ages, growth becomes less efficient, leveling off when the stand reaches maturity.

At the beginning of each simulation, a one-hectare stand is stocked with a specified number of seedlings, and as the stand matures, the population is thinned following the -3/2 power law which is observed in terrestrial plant populations.[1] The model keeps track of many state variables that describe the stand, including leaf area index, basal area, and biomass of the various tree components. Stem volume is the quantity of interest for the timber valuation, so the stem biomass is converted to a volume and output to the economic model. The model runs in MATLAB, using code adapted from the Visual Basic implementation included with 3PGpjs (Sands 2001), a user-friendly interface for 3-PG.

Species distributional changes were simulated using the BIOMOD species distribution modeling software. BIOMOD executes multiple species distribution models using a common set

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[1] A self-thinning relationship has been observed in a broad range of plant species, in which a unit decrease in density will occur for every 1.5-unit increase in biomass.

of species presence and absence data from multiple sources (e.g., Forest Service, National Park Service, California Fish and Game) in conjunction with environmental data. Species distribution models implemented in BIOMOD include generalized additive models (GAM), Generalized Linear Models (GLM), and Classification and Regression Trees (CART). These multiple species distribution models are combined into a single consensus model using a principle components analysis. Environmental data included both climate (annual temperature range, mean temperature of the driest quarter, mean temperature of the coldest quarter, precipitation seasonality, precipitation in the wettest quarter, and precipitation of the warmest quarter) and soil variables from the State Soil Geographic Database (STATSGO; available water capacity [fractional volume of water per volume of soil], soil depth [in meters, m], pH, salinity [millimhos per centimeter, or mmhos cm^{-1}] and depth to water table [m]).

Relative abundance of species was calculated from the species distribution models. Environmental data were extracted for each predicted presence point and subjected to a z-transformation. The transformed values were summed across all variables. The absolute values of these data were rescaled from 0–1 to provide a measure of relative abundance for each 1-km cell. These values were used as the metric for scaling abundance across the landscape for each species in the growth model.

2.2.2. Species and Domain Selection

The final economic valuation is intended to encompass all privately owned timber land in California, so the analysis is restricted spatially by land ownership and management type, as well as by timber species distributions. Starting with a statewide grid at a resolution of 1/8 degree (~12.5 km), we use cells that are classified as “private” and “working” by the California Department of Forestry. These lands are filtered further by species distributions obtained from the BIOMOD model (Thuiller 2003). If any timber species is predicted to occur within a cell at any time between the present and 2080, that cell is included in the analysis. A total of 791 grid cells are selected for modeling using this method.

Douglas Fir, Ponderosa Pine, Redwood, and Western Hem-Fir collectively account for over 92% of harvest value on private lands in California, according the California Board of Equalization Timber Tax Database (Spero 2006). Western Hem-Fir is a combination of Western Hemlock and five true fir species, whose wood is considered interchangeable for tax purposes. We model Western Hemlock to capture some of the value from this aggregation of species. Thus, the four species used for productivity modeling are Douglas Fir, Ponderosa Pine, Redwood, and Western Hemlock.

2.2.3. Species Parameters

Species physiological parameters in 3-PG fall into several broad categories, the most important of which relate to: light capture, photosynthesis, biomass partitioning, and impacts of age on productivity. Some of these can be obtained from field measurements of tree growth, stand densities, and other observable quantities, while others must be estimated or derived from basic physical processes. In this study, species parameters are taken from prior, species-specific studies: Law et al. (2000) for Ponderosa Pine; Coops and Waring (2001) for Douglas Fir; and Koch et al. (2004) and Busing and Fujimori (2005) for redwood. Resulting growth rates were calibrated against plot data from the Forest Inventory and Analysis (FIA) program of the U.S. Forest Service.

2.2.4. *Climatologies, Emissions Scenarios and Site Parameters*

Climate data are provided by the California Applications Program / California Climate Change Center (CAP / CCCC) and consist of monthly values for minimum temperature, maximum temperature, and precipitation for the years from 1950 to 2099, The time series in this data set are derived from individual runs of several GCMs and have been downscaled to a resolution of 1 / 8 degree for the State of California. The growth simulations in this study use two of the available models: the National Center for Atmospheric Research Parallel Climate Model version 1 (PCM1) and the Geophysical Fluid Dynamics Laboratory Climate Model version 2.1 (GFDL). We smooth the data using a 31-year moving average filter, producing monthly values for the years 2055 through 2085.

Emissions scenarios for both GFDL and PCM1 were Intergovernmental Panel for Climate Change (IPCC) A2 and B1 emissions scenarios. The A2 scenarios correspond most closely to current emissions pathways. B1 scenarios are low emissions pathways premised on absence of climate policy intervention, but it is highly unlikely that these pathways will be realized without such intervention. A2 scenarios more accurately represent the climate changes California is likely to face, and in fact may underestimate impacts, as actual current emissions trajectories actually exceed those predicted by the A2 scenario.

The soil parameters are based on simplifying assumptions about soil depth, composition, and fertility. Soil texture is assumed to be sandy loam, and available water capacity [mm, depth equivalent] is derived from the STATSGO soils dataset. Soil fertility data are generally poor, and there are few quantitative guidelines for choosing a fertility ranking (Landsberg et al. 2003), but Swenson et al. (2005) modeled fertility values between 0.19 and 0.53 for western Oregon, which compared well with field measurements. Soil fertility rank for all sites in this study is taken to be 0.4.

Monthly radiation data are calculated from slope, aspect, latitude, and elevation using the method in Coops et al. (2000). Slope, aspect, and elevation data are all derived from a U.S. Geological Survey digital elevation model (DEM) at 1-km resolution.

2.3. Economic Model

2.3.1. *Description of the Model*

We begin by considering a single site sufficient to support a single mature tree; this is our decision unit. The forester has control over the rotation period and the species to replant after harvest. We assume foresters are economically rational and thus seek to maximize the forest land’s net present value. In order to make a rational decision, the forester knows the site characteristics, such as soil, temperature, precipitation, and aspect. These site characteristics inform the forester about the growth potential for any potential species at that location.

In an environment where site characteristics remain constant over time, the economically rational forester would sit down at the beginning of his management tenure and make two decisions. First, for any potential species of tree, the forester would calculate the optimal rotation period that would maximize the total net present value of all future harvests. Given the optimal rotation periods, the forester can then make this second decision, the “best” species to plant at that site. Here “best” is defined as the species that provides the greatest profit from all future harvests. Because conditions do not change in a static environment, the best species now will also be the best species any time in the future. In a static environment, the forester picks a rotation period and a single species of tree to replant and sticks with his decisions forever.

Climate change introduces dynamics into this story. The forester's decisions now involve extremely complex tradeoffs. The features of this problem that make it particularly complicated include:

- Changes in site suitability for major timber species
- Growth parameters that are species-specific and time-varying due to climate change
- Prices that change over time (this is supported by the literature on global timber markets under climate change scenarios)
- Ability to incorporate carbon payments for sequestration

Now that site characteristics are changing over time, it is incorrect to assume the forester responds in a static way. We develop a new adaptive approach to allow for the forester's decisions to change over time.

Three Management Scenarios

Two adaptive responses the forester can choose from are changing the rotation period and changing what species of tree to replant. While there is likely to be significant heterogeneity across landowners, we can immediately consider three management scenarios.

Naïve Management: The least generous assumption to the landowner is that he is ignorant of climate change and continues to be, and so executes a rotation and species replanting strategy that assumes status quo climate in perpetuity. This Naïve management scenario will assume the forester does not change either rotation period or replanting species, and it would likely return relatively lower profits, since it fails to account for changes in productivity and species suitability that would occur as a result of climate change. This option has no choices—the forester's static rotation period strategy is applied in perpetuity.

Rotation Management: The Rotation management option is more adaptive than Naïve management in terms of the landowner's ability to foresee climate change. Here the landowner will change the rotation period to maximize profit but does not have the full adaptive foresight to anticipate changing site suitability and change species to be replanted. Thus Rotation management introduces two basic choices to be made each year:

1. Cut the current stand and replant the same species.
2. Let the current stand grow another year.

Optimal Management: The most generous assumption is that the forester has perfect foresight regarding changes to the climate, and can anticipate those changes in their rotation and replanting decisions. The Optimal management scenario will assume the forester changes both rotation period and replanting species according to projections of climate change impacts. This will maximize present value of profits under a climate change scenario, thus placing an upper bound on the value of the patch. Our new adaptive model takes this complicated economic problem and condenses it to the annual choice between three options:

1. Cut the current stand and replant the same species.

2. Cut the current stand and replant with a different species.
3. Let the current stand grow another year.

Under options 1 and 2, the forester reaps the current value of the timber and of the stream of carbon payments, though he incurs a replanting cost. Under option 3, the forester obtains no immediate payoff, but knows that he will obtain a payoff in the future.

Solving the Recursive Problem One Site at a Time

The optimal option is the most complex to model. In this option, each site is optimized separately, and the output is a "value function" for each patch. The general three-choice, recursive problem is amenable to an optimization technique called dynamic programming, which we implement in MATLAB. The state variables are the age and species of the stand, and we must explicitly account for calendar time, since it indicates changes in growth and price which are driven by climate change. Every year, we find the values across an age range from 0 to 100 years old and across four species (Douglas Fir, Ponderosa Pine, Redwood, and Hemlock). The "value function" for each year is a collection of values across all ages and all species. The value function provides the net present value of optimized rotation and replanting decisions for any given starting condition up until the terminal period. In MATLAB, we generate a value function each time period. By iterating backwards from the terminal period to the starting period, we are able to generate the value function for the starting year. By comparing the value functions in the starting year under the climate-change and no-climate-change scenarios, we are able to predict the effect of climate change on a patch of land.

Modeling the rotation option follows the method used for optimal management, but with choice at each timestep limited to cutting or allowing continued growth (adjustment of rotation interval).

The model for the Naïve option simply follows the initial species and rotation decision for the entire period of the model run.

Novel Features: Our adaptive approach provides the flexibility to incorporate new features. Others have estimated the impacts of climate change on the forestry sector. Our analysis extends those approaches in several dimensions, including:

- Species-specific growth rate changing over time
- Species-specific price of timber that changes over time
- Ability to adapt by replanting with a different species
- Ability to account for the effect of carbon credits on harvesting and replanting decisions
- Ability to incorporate urban development with a land use projections layer. If we see that a pixel of land is projected to change from forest to housing, we simply change the terminal period to match the switching date. This will, in general, have an effect on decision making. If a pixel is not projected to change, then the terminal period will be far out into the future.
- "Intuitive" recursive, dynamic optimization approach to a traditional, static optimization problem.

Assumptions

Key assumptions in our model involve discount rate, replanting cost, and harvest cost. Discount rate is based on likely long-term values, while replanting cost and harvest cost are estimated from the literature as follows:

Discount Rate: We assume a constant discount rate of 5%.

Replanting Cost: We assume a constant replanting cost of $988 per hectare, which is converted from Mendelsohn's $400 per acre figure (2006). This holds for all species.

Harvest Cost: We assume a constant harvest cost of $31 per cubic meter. The harvest cost directly decreases the price per cubic meter of timber.

Integration with Biological Model

To make the output from the biological growth model useful for our economic model, we take the biological output, which is a series of annual volumes from age 0 to age 100, and fit a functional form to generate a growth curve: Volume (age) = exp (alpha-beta / age), which is commonly used to model timber growth. The parameters alpha and beta are site, species, birth year, and climate scenario dependent. The renormalization ratio is multiplied by Mendelsohn's average volume function (Mendelsohn and Smith 2006) to get a species-specific, site-specific, establishment year-specific, and climate change scenario-specific volume for each tree. Another way of saying this is we took our variation in volume relative to our average volume and rescaled it to Mendelsohn's average volume to get new volume function parameters. The end result mathematically is a change in the alpha terms while preserving Mendelsohn's original beta.

2.3.2. Global Timber Prices

There is a small but growing literature on global timber prices under climate change. We adopt the annual changes found in Sohngen et al. (2001) from 2000 to 2080. The prices are derived under five scenarios: Baseline (no climate change) and two variants each of the Hamburg and University of Illinois at Urbana-Champaign (UIUC) climate change models. We use the UIUC model, regeneration variant for our price series, and we assume that California landowners are able to sell on the global timber market. The UIUC regeneration variant is intermediate among the models developed by Sohngen et al. No climate change price model is more than 10% greater or lesser than this variant at any timestep, and all are substantially different than the no climate change price curve. While in practice, different GCMs and different emissions scenarios would have unique global price curves, we use this single price scenario to represent all GCMs and all emissions scenarios, because the differences between these curves are small relative to the price effect of climate change.

Figure 2.3.1 shows the price series for lumber under climate change and a baseline scenario. Under these assumptions, global output of lumber increases in both cases, but more so under climate change, which drives down the price over time under climate change relative to no climate change. In 2080, this price series predicts about a 35% increase in the price under climate change and about a 62% increase in price with no climate change.

Using the Sohngen et al. global timber price projections, we calculate the change in global price and applied the change to each species' specific price (obtained from State Board of

Equalization (2007). For Douglas Fir, Ponderosa Pine, Redwood, and Western Hemlock, we assume midsize volume per log and take the average harvest value across all timber value areas in California. Dollar values for statewide gains or losses were obtained by multiplying percentage gain or loss by current (2007) harvest value.

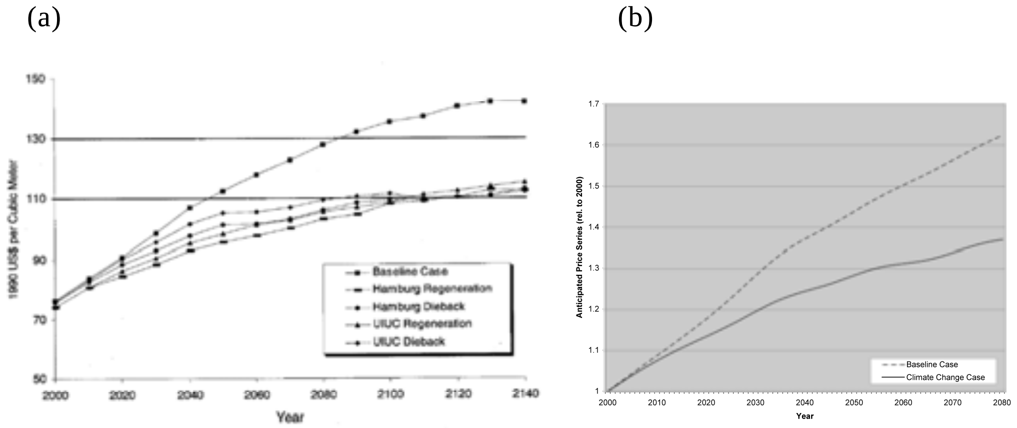


Figure 2.3.1. Global timber prices series over time

(a) Global price series from Sohngen et al. 2001; (b) price series derived for this study

2.3.3. Carbon Payment

We follow the economics literature and model the carbon payment as a fixed annual payment on the increment in volume of timber in a patch. This approach does not simulate actual markets or specific sets of market rules, such as those that set the conditions for measuring baselines or increments of carbon. There are many potential sets of rules currently being discussed in the policy arena, and it would be difficult to select one with confidence. Instead, giving value to carbon stocks, rewards deviations from a status quo trajectory (the ultimate goal of all proposed market rules) without having to define the specific rules that measure such deviations. The amount of carbon sequestered is proportional to the change in volume of the tree in each period, and consequently, so is the payment. The present value of carbon payments over one rotation interval of length T is the discounted sum of all the incremental values of carbon added each year. Following van Kooten (1995), we can represent the present value mathematically as:

$$\int_0^T p^c \alpha v'(t) e^{-rt} dt$$

Where p^c is the price of carbon per unit of sequestration, and the coefficient α both translates volume into carbon and accounts for the fact that not all carbon is actually sequestered. Integrating by parts, we obtain:

$$p^c \alpha v(T) e^{-rT} + r p^c \alpha \int_0^T v(t) e^{-rt} dt$$

This payment is interpreted as follows: the forester obtains two payments. First, he receives a final payment at the time of harvest (*T*). Second, he receives a payment on the stock of carbon each year. The first payment is the added value from permanently storing carbon. The second payment is a rental equivalent of holding the carbon out of the atmosphere for each year in which it is stored, priced at $r*p^c$. So the forester "rents out" carbon storage space in his trees each year for the price of $r*p^c$ and at the end of the harvest cycle, he sells the carbon he owns at the price of $p^{c.}$ Instead of paying for carbon and taxing emissions, we can see it as a story of foresters having property rights to the carbon stored in their trees.

To incorporate this carbon payment into our model, we convert the present value of carbon payments to current value of carbon payments and add this current value onto the timber value whenever the forester decides to cut. Thus, the carbon payment is capitalized up to the harvest date, and it is *as if* the forester receives two payments at the time of harvest: a payment for the value of the logs and a payment for the value of the carbon that was sequestered during its lifetime. As an internal case study, we focus on just one county, Del Norte, and run four management scenarios: Naïve, Rotation, Optimal, and Optimal with Carbon Payments.

One issue with carbon sequestration is at the time of harvest, a proportion of the tree will decay and the carbon will be reemitted back into the atmosphere, captured here by the parameter α. Other papers have approached this problem by requiring an emission liability at the time of harvest. We make a simplifying assumption that only a certain percentage of the carbon sequestered will be "permanently" sequestered. Thus the conversion factor will take into account both the amount of carbon sequestered given a certain volume of biomass and the amount of carbon that will be permanently sequestered. Thus the conversion factor will take into account both the amount of carbon sequestered given a certain volume of biomass and the amount of carbon that will be permanently sequestered. In our simple hypothetical carbon market example, we assume the price of carbon dioxide emissions to be $20 per ton and the conversion factor to be .6 tons of carbon dioxide permanently sequestered for each cubic meter of wood.

These simplifications allow us to take an approach to carbon valuation that is similar to that found in the economics literature. This economic approach contrasts to a rule-based or market approach in which one would attempt to simulate the effects of one of several possible sets of rules that may be used to implement carbon markets. Our simpler assumption has the advantage that it is more generalizable. We have employed it specifically to avoid outcomes that may be dependent on a specific set of rules, since it is impossible to know exactly what rules will be agreed upon for either state or global carbon markets.

The value of harvest at any given time integrates both the value of timber and the carbon payment. As noted above, this complex dynamic optimization problem is solved with a numerical approach called value function iteration. The value function iteration occurs by iterating backwards from a terminal date that is far enough into the future as not to effect decisions made during the of the study period from 2000–2080. We choose a terminal date of 2200 and assume by then that the value of trees in the ground consists solely of the harvest value and has no replanting value component. Because our growth parameters cover birth years over the range 1900–2080, trees born after 2080 are assumed to have the same growth parameters as 2080 trees. Likewise, as our price range runs from 2000–2080, prices after 2080 are assumed to stabilize at 2080 levels.

In addition to measuring the overall effect of valuing carbon, it is important to assess the effects of particular sets of market rules on individual behavior and on the distribution of carbon payments. The interaction of carbon and timber markets to produce production and landscape outcomes is a further field worthy of research. Our analyses cannot shed light on these important issues, but we hope to inspire additional research into these important questions by laying additional groundwork for future, more complex studies.

2.3.4. Fine Scale Test

To test the spatial and quantitative effects of sampling the landscape at the scale of the state assessment climatologies, we conducted a much finer grain run of the biological and economic models. This test with generic global climate projections was conducted to verify that the results of the simulation were not strongly scale-dependent. A downscaled global climatology for two GCMs at 1 km was obtained from the Worldclim website. Two GCMs (HadCM3 and CCM) and two emissions scenarios (A2 and B2) were used to drive the biological models. These GCMs from the Third Assessment Report series of the IPCC are the only climatologies available for California at this scale. The results of the biological modeling were then input to the economic model using the same methods employed for the 1/8 degree climatologies. At the 1-km scale, the model simulates 59,884 sites statewide, while at the 1/8 degree scale, 791 sites are simulated. It is not possible to use these fine grain models for the state assessment because the timeframes, GCMs and IPCC series would not match those of other state assessment studies.

The spatial pattern in value change was similar in both the 1-km and 1/8 degree outputs. Percentage change and aggregate change were of the same order of magnitude for the climate change price series. The fine scale results yielded more negative values for the no climate change effect on prices scenario, increasing confidence that decreasing values are a robust effect of climate change and not wholly dependent on price declines due to climate change. The results of the fine scale test therefore give confidence to both the coarser, 1/8 degree results presented here and the conclusion of value decline, although precise comparisons are impossible because the input climatologies are not identical. Figure 2.3.2 illustrates the output of the fine scale test.

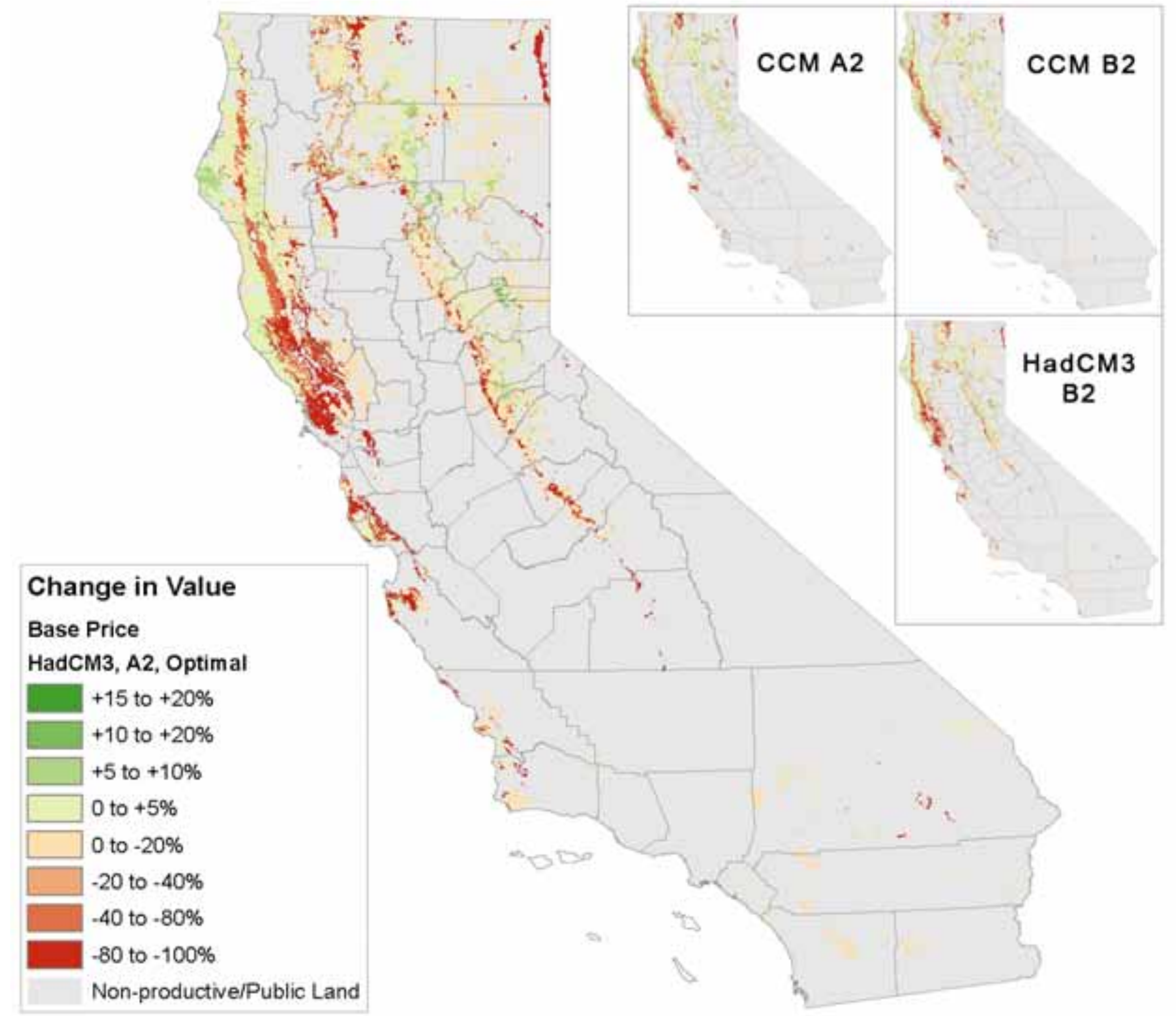


Figure 2.3.2. Example of fine-scale test results. Percent changes in timber value due to climate change for 59,884 sites across California. The values are computed using the baseline pricing scheme for the global timber market. No strong scale-dependence in results was observed.

3.0 Results

We now turn to our results. Because our model runs span a large factorial of scenarios (e.g., climate change scenarios, management scenarios, price series), we separate our results into seven sections, and present the salient conclusions from each topical area. Our results presentation focuses on the A2 emissions scenario, for several reasons. The A2 scenario is the closest scenario to current emissions pathways. The B1 scenario results show spatial patterns similar to the A2 results but with more muted change. To reduce repetition, only A2 spatial results are shown in the figures. There are, however, substantial differences between A2 and B1 statewide economic losses, so both A2 and B1 results are presented in our statewide impact results.

3.1. Value Change Assuming No Effect of Climate Change on Prices

The value of California timber is influenced by two key factors that change under climate change: price and production. We examine the interaction of these factors in the next section. In this section we examine changes in value due to changes in production alone. In this scenario, prices increase as if they were independent of climate change (baseline prices). While this is very unlikely to be the case, it allows us to isolate the effect of biological changes on production.

The two climate change-driven factors that influence production in our model are changing species ranges and alteration in productivity. The ranges suitable for growing commercial timber species will shift as climate warms and precipitation changes, which in turn affects the potential species mix at a location and the value of harvest. The productivity of individual species can also change, again affecting the value of harvest at a location. The combination of species ranges and productivity, absent exogenous price signals, could increase or decrease value at any given location.

In general, we may expect value increase due to warming temperatures leading to more rapid tree growth. With warmer temperatures, biological processes accelerate. In trees, this leads to more rapid growth and a larger annual growth increment. Assuming the quality of the wood produced is maintained and price is not influenced by climate change, this will result in increasing harvest values at a wide variety of site conditions and species mixes.

This expectation is generally borne out in our results (see Figure 3.1.1). Value change in the PCM1 scenario is generally neutral or positive. Value change in the GFDL scenario is more positive, with gains outbalancing declines and areas of modest or neutral change. There is a much larger range of values in the GFDL results, from strongly positive to strongly negative.

There is no simple productivity-related explanation of these patterns. Growth is heavily influenced by precipitation, soil type and their interaction, as well. Moisture deficit may reduce annual growth, production and potential value. Declining snowpack has been implicated in the upslope retreat of pine species due to climate changes that have already occurred in California. Similar or other precipitation-related effects on growth will interact with the effects of temperature to determine the net increase or decrease in productivity at a site.

The expectation from shifting species ranges is even more complex. High value species may either expand or contract their ranges in response to climate change. In general, species will shift ranges upslope, which may result in shrinking ranges, because mountains have progressively less area at upper elevations.

The species range shift models indicate that important conifer timber species are likely to expand their ranges at the expense of species of low commercial importance. In particular, pine species may expand their ranges, replacing oak species in many areas. This shift to higher value species in some locations is a major driver of the differences observed in value change across regions, particularly in the Northern Sierra in locations such as eastern Amador county.

The realized change in value depends on the interaction of management with these productivity and species mix changes. A land manager optimizing with respect to climate change will capture more of this increased value than will a manager following past practices. For this reason, the strongest gains in value are seen in the optimal management option, in which timber managers can adjust both rotation interval and species mix to respond to climate change (Figure 3.1.1).

Price effects may also play a role. While the price scenario presented in this section assumed no effect of climate change, prices were not static. Increasing global timber prices may interact with productivity effects to produce stronger positive effects on timber value. The modeling used in this study simulated the effects of both productivity and range changes, which were modeled separately, as described in the methods. The combined influence of these changes was assessed in the economic model, with the final output denominated in value of harvest. This value is aggregated through time into a single figure, net present value. This value is the important both as an index of harvest value, and as the value of land that, if exceeded by other land uses, might result in the conversion of timberlands to other land uses—such as housing or agriculture. We present our results as the relative change in this net present value due to climate change.

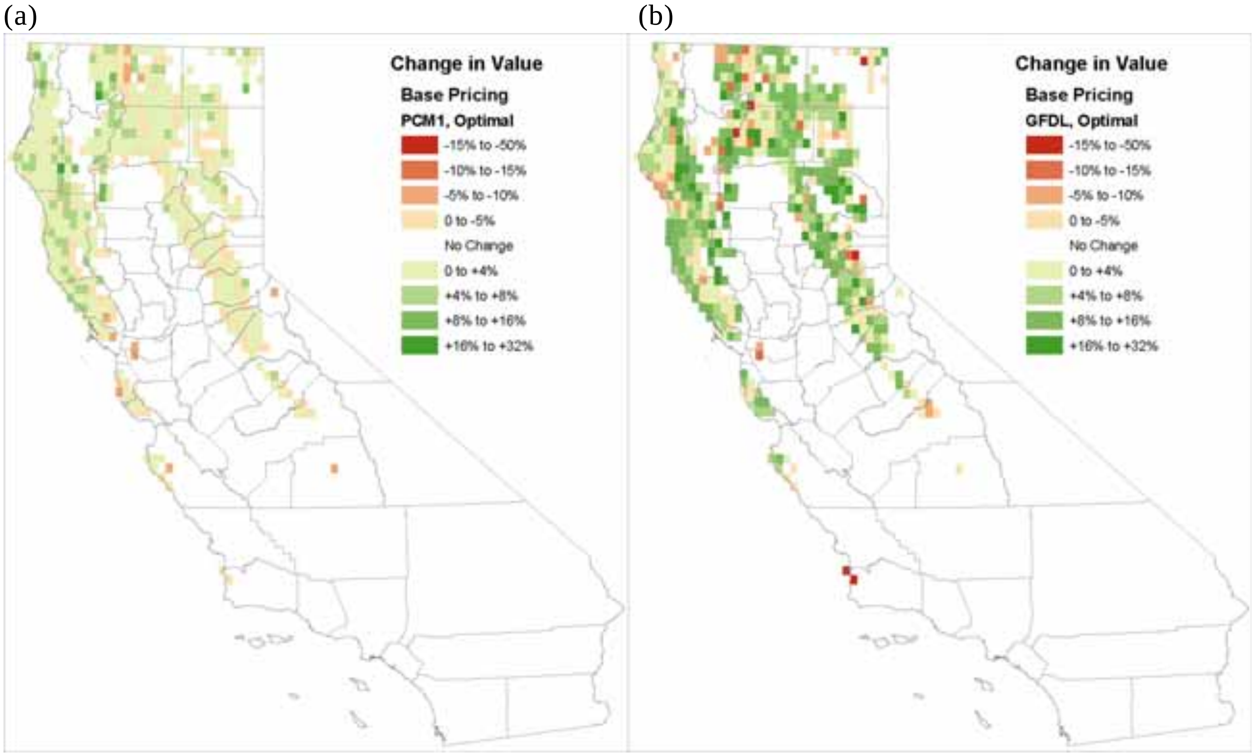


Figure 3.1.1. Percent changes in timber value due to climate change for 791 sites across California, baseline (no effect of climate change) price series and optimal management option.

(a) PCM1 A2 climate scenario relative to a case in which no climate change occurs, (b) value change under the GFDL A2 climate scenario using the same color scale.

High spatial variability within scenarios is a major result of note. The spatial variability in response within climate scenarios is much stronger than the variability between climate scenarios. The warmer, high emissions scenarios under both GCMs showed more negative changes in value than do the low emissions (cooler) scenarios. However, the difference between high and low regional values within these scenarios is always higher than the between-scenario differences. Understanding the causes of this spatial variability are important in understanding how to manage timberlands and build policy for climate change.

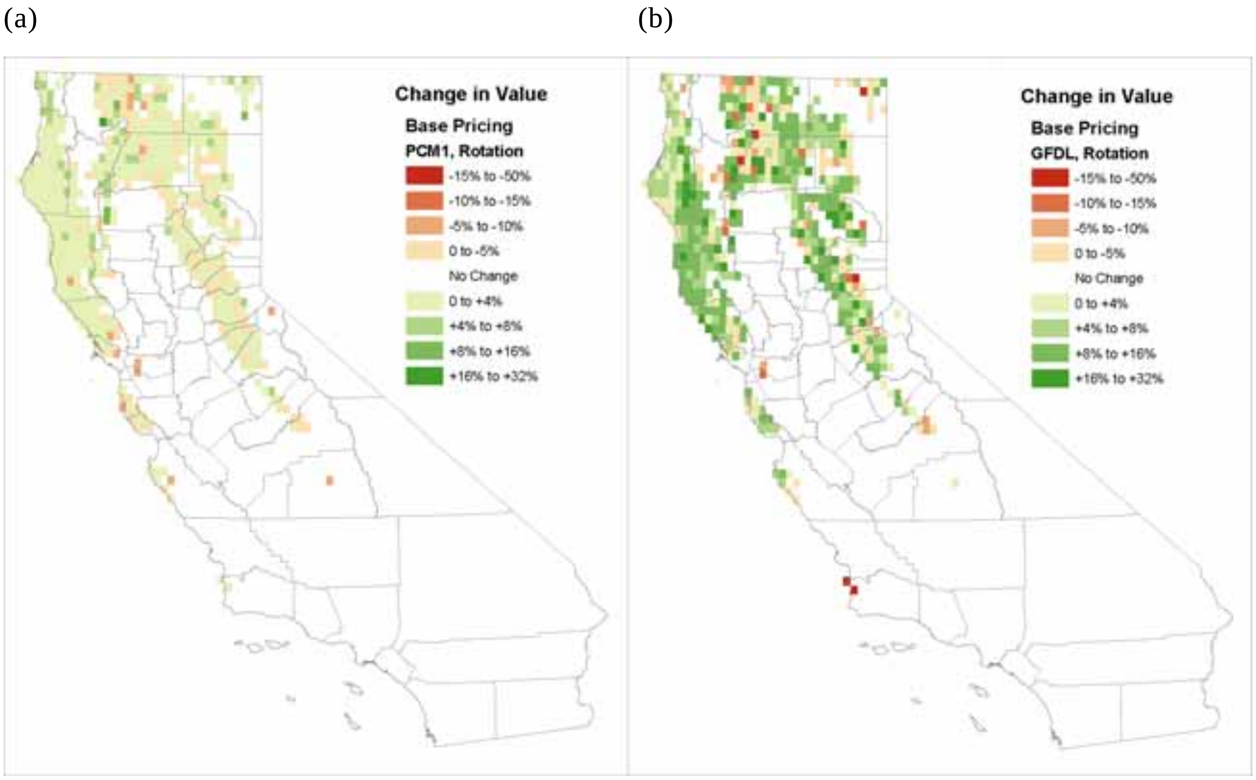


Figure 3.1.2. Percent changes in timber value, baseline price series and rotation management

(a) PCM1, baseline price series, A2, rotation management. (b) GFDL, baseline price series, A2, rotation management.

Some of the decreases in value are severe, despite general positive trends. In these areas, cessation of timber harvest or conversion to other land uses is likely. However, exploration of these implications relies on a more realistic price assumption. Climate change will affect timber prices. The next section explores the implications of this more likely model of value change.

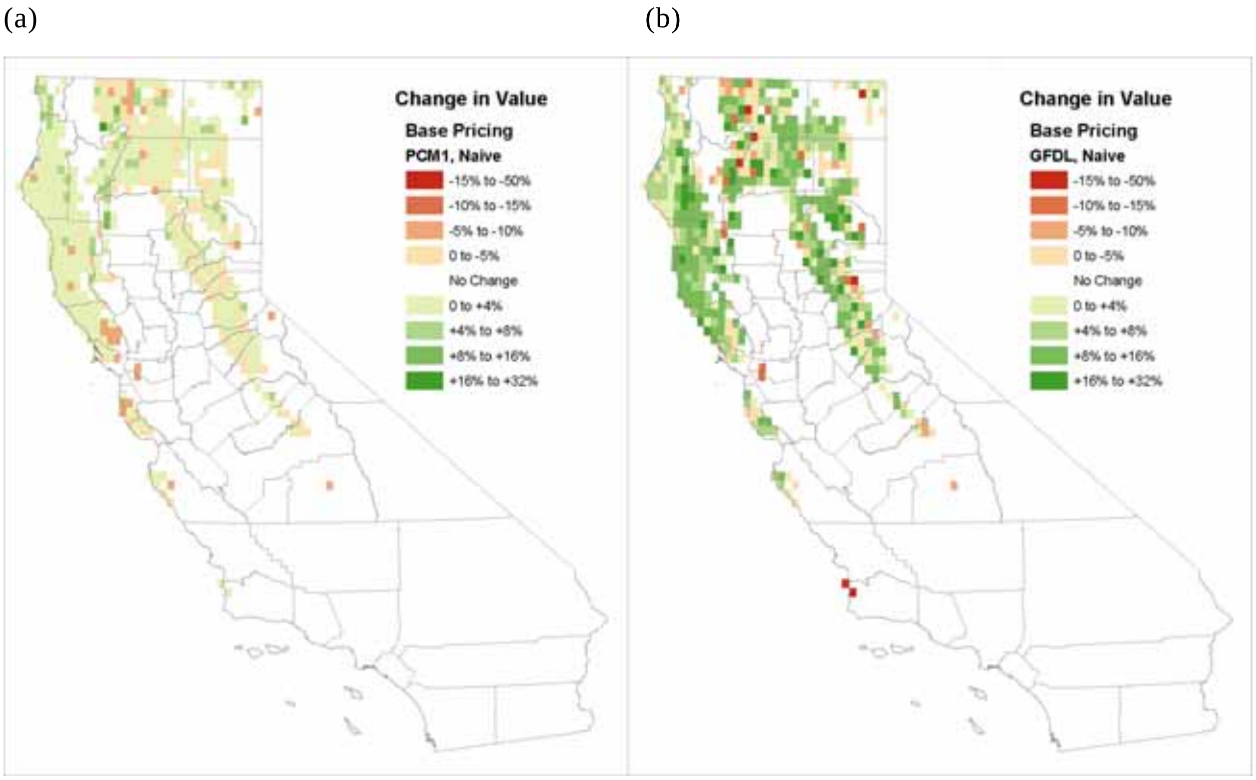


Figure 3.1.3. Percent changes in timber value, baseline price series and naïve management option

(a) PCM1, baseline price series, A2, rotation management; (b) GFDL, baseline price series, A2, rotation management.

The differences between management scenarios are minor relative to the spatial variation within scenarios. More adaptive management lessens areas of value decline, especially in areas of Mendocino and Humboldt counties. These differences may be important when combined with consideration of areas actually harvested (see below).

3.2. Value Change Incorporating Climate Change Effect on Prices

Productivity and range changes combine with price to determine the change in value at a particular location due to climate change. Global prices are influenced by many factors, including climate change. Because productivity is expected to increase in many high latitude timberlands currently limited by low temperatures, the global price of timber will be affected by climate change. Increasing productivity means increased timber supply, leading to price depression. Demand for timber will continue to increase, so timber prices will still increase, but climate change will result in lower prices than would otherwise occur.

The economic model employed in this study incorporates a dynamic price element, which, when combined with the dynamic range and productivity elements, gives a relatively complete picture of value change due to climate-related factors. Here we present the results of this model emphasizing the spatial distribution of value change across the state. We present the result of only one management option to simplify the comparisons.

Figure 3.2.1 shows the spatial distribution of value change including climate change effects on price. These results, in contrast to the biological effects, show strong declines in nearly all areas. The PCM1 scenario, which showed mainly neutral biological change, is strongly affected by the relative decline in price. The GFDL values are less negative, but most of the positive biological change in this scenario has been cancelled out.

As with value change due to biological changes alone, there is high spatial variability. Again, there is more spatial variability within the scenarios than there is difference between climate scenarios.

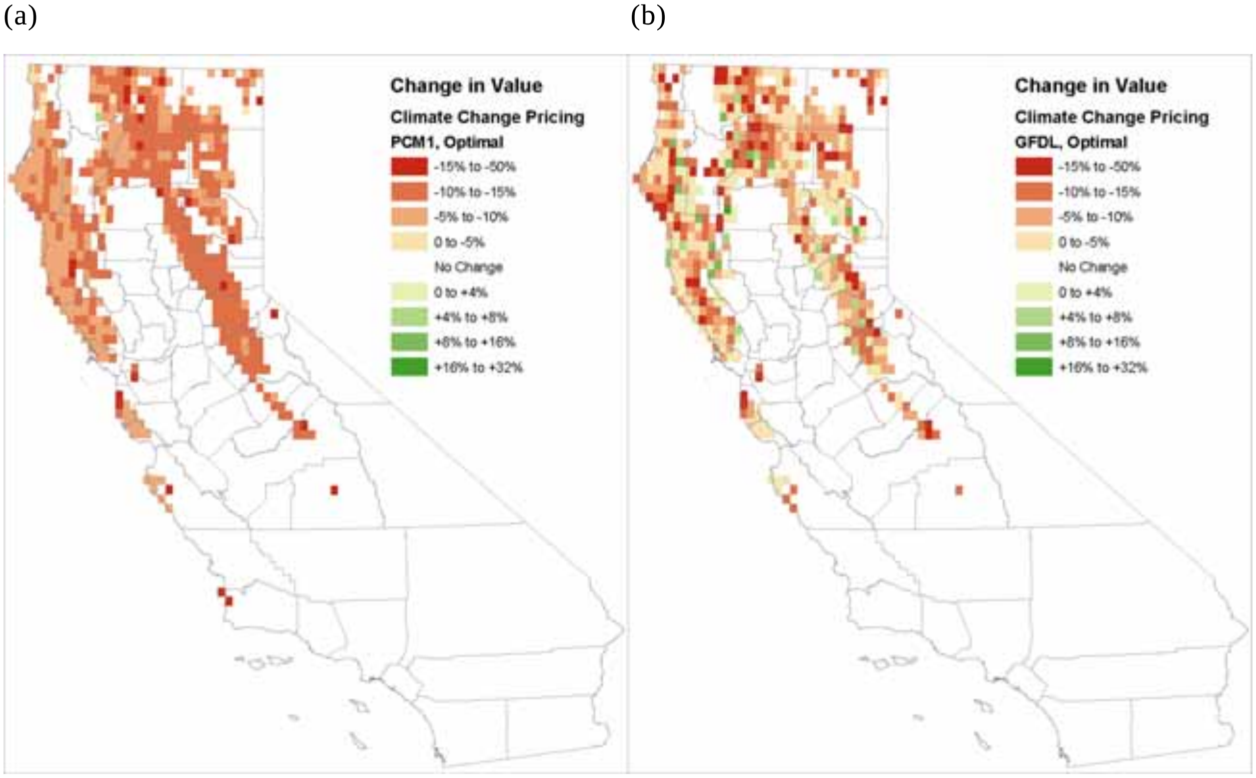


Figure 3.2.1. Percent change in value under climate change price series. a) PCM1, climate change price series, A2, optimal management. b) GFDL, climate change price series, A2, optimal management.

Declines dominate these spatial outputs. Declines of 10%–15% are common in the PCM1 scenario, while declines of 15%–50% are not uncommon. In the GFDL scenario, large declines are observable in many locations, while increases in value are so rare that they are difficult to discern visually. Many areas show little or no net change in value. Areas of strong decline are seen just inland along the Mendocino coast, in the Santa Cruz mountains, in parts of the Sierra, and in the extreme north of the state.

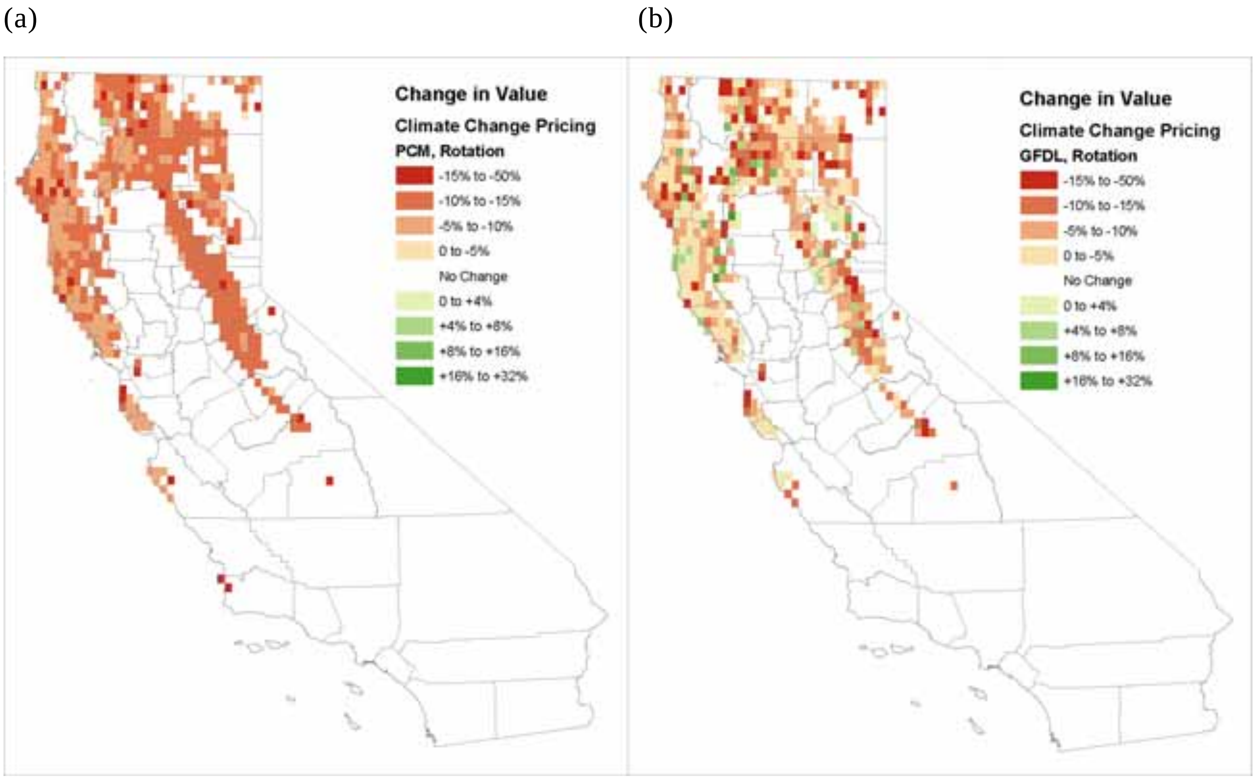


Figure 3.2.2. Percent change in value under climate change price series and rotation management

(a) PCM1, climate change price series, A2, rotation management; (b) GFDL, climate change price series, A2, rotation management.

The patterns of decline are determined by interactions of price, productivity, and species range. Locations in which productivity and species mix remain relatively constant are vulnerable to declines due to the relatively lower price resulting from climate change. Conversely, areas in which productivity increases and shifts to more valuable species occur, these increases tend to offset the lower price seen with climate change.

These effects produce changes in land values that are highly spatially variable between regions of the state and between individual locations, even in close proximity. This increases the likelihood of strongly patterned changes in land use, such as conversion of timberland to residential use.

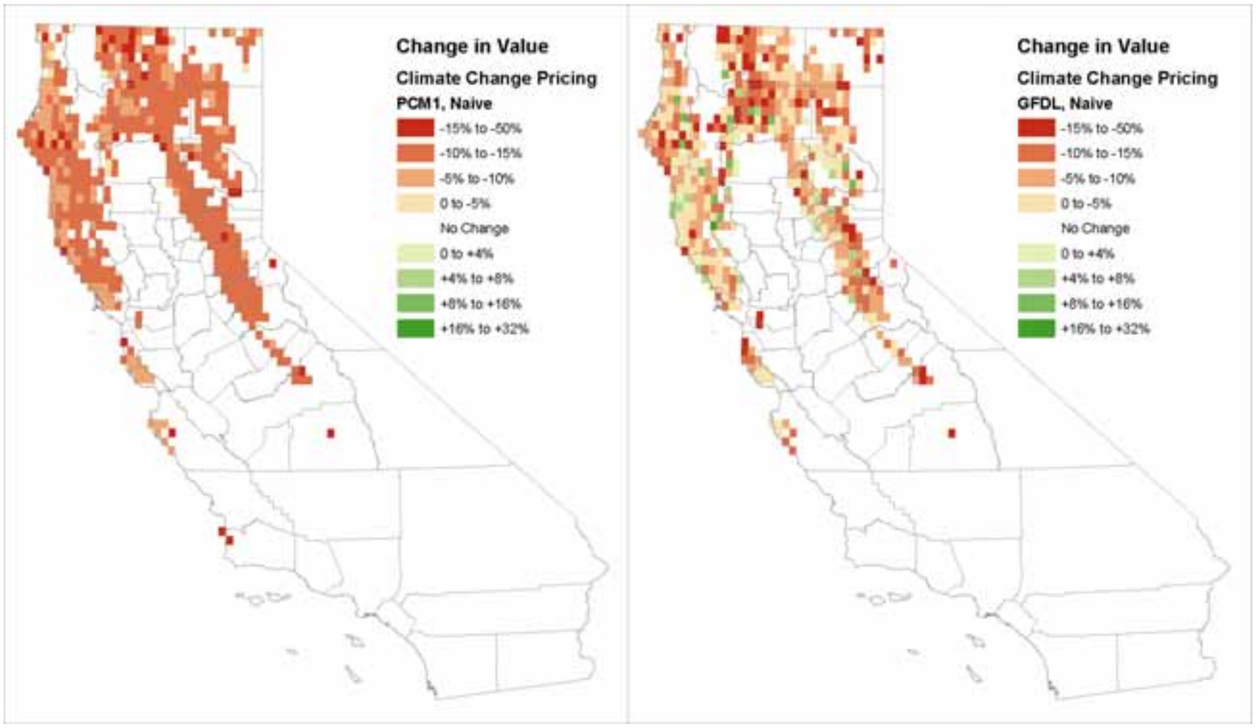


Figure 3.2.2. Percent change in value under the PCM1 and GFDL climate scenarios and naive management

(a) PCM1, climate change price series, A2, naïve management; (b) GFDL, climate change price series, A2, naive management.

Differences between climate scenarios have significant implications for these patterns of change. For instance, areas north of San Francisco and bordering the Central Valley see substantial declines in value in the PCM1 scenario. That will make these areas more vulnerable to conversion to residential use, a trend that is already significant in these parts of the state. This pattern is much less pronounced in the GFDL scenario.

Locally, declines in harvest or conversion to other uses may be severe, following the significant subset of localities which see major declines in value. The loss of value may have major implications for land use, as declining timber values confront rising land values for agriculture or housing, as will be discussed below.

The remainder of this report explores the implications of these changes for individual counties, the effects of management on these outcomes, and their implications for land use and policy.

3.3. Aggregate Climate Change Effects by County

This spatial disaggregation discussed in the previous section provides an important characterization of the *potential* effects of climate change, but it may obscure the *most likely* effects. Under the assumption that parcels currently under forest production are the parcels that will remain under forest production, we are able to weight each site in the disaggregated map by an estimate of the current percentage under timber production. This results in county-level estimates of decline in value. Since some counties may have high percentage changes but low timber production, we then aggregate all sites within the state to determine an overall loss in value, which is then apportioned to each county based on its contribution to the total.

The greatest proportion of total loss occurs in Mendocino, Humboldt, and Del Norte counties, (Figure 3.3.1) reflecting the large proportion of the state's overall timber value arising in these counties. For both climate projections, the declines in value within these three counties encompass over 50% of the loss in timber value statewide.

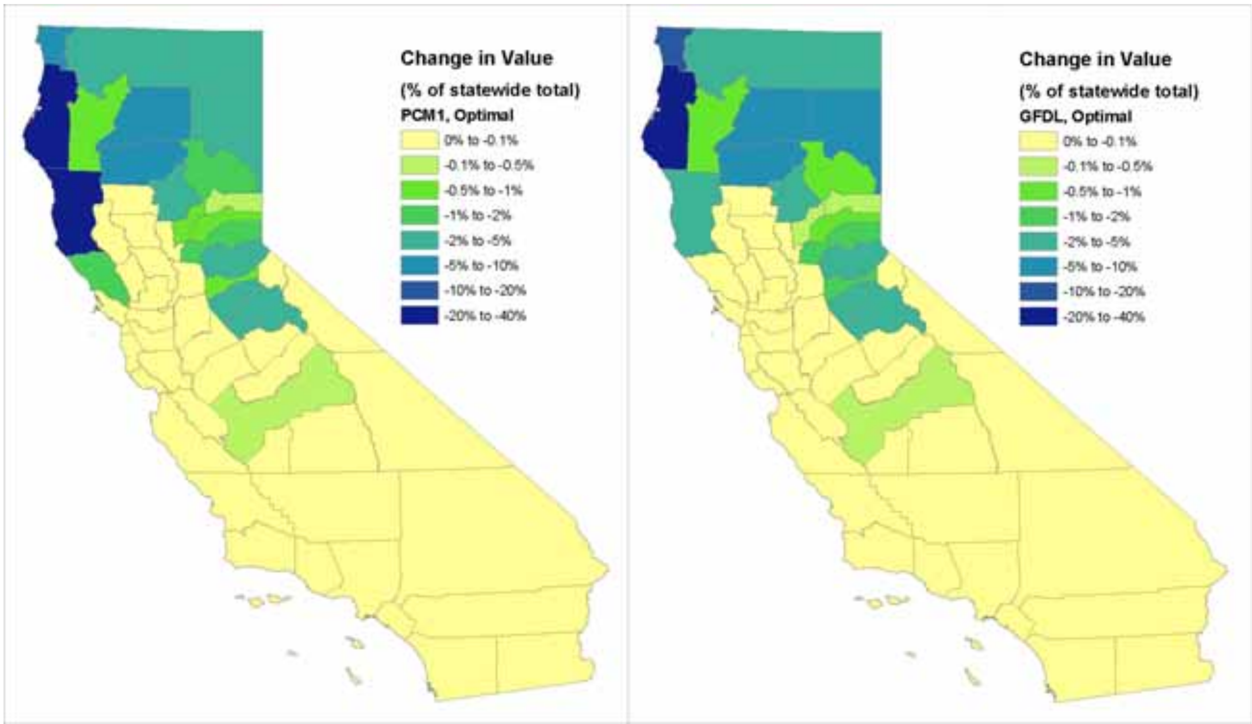
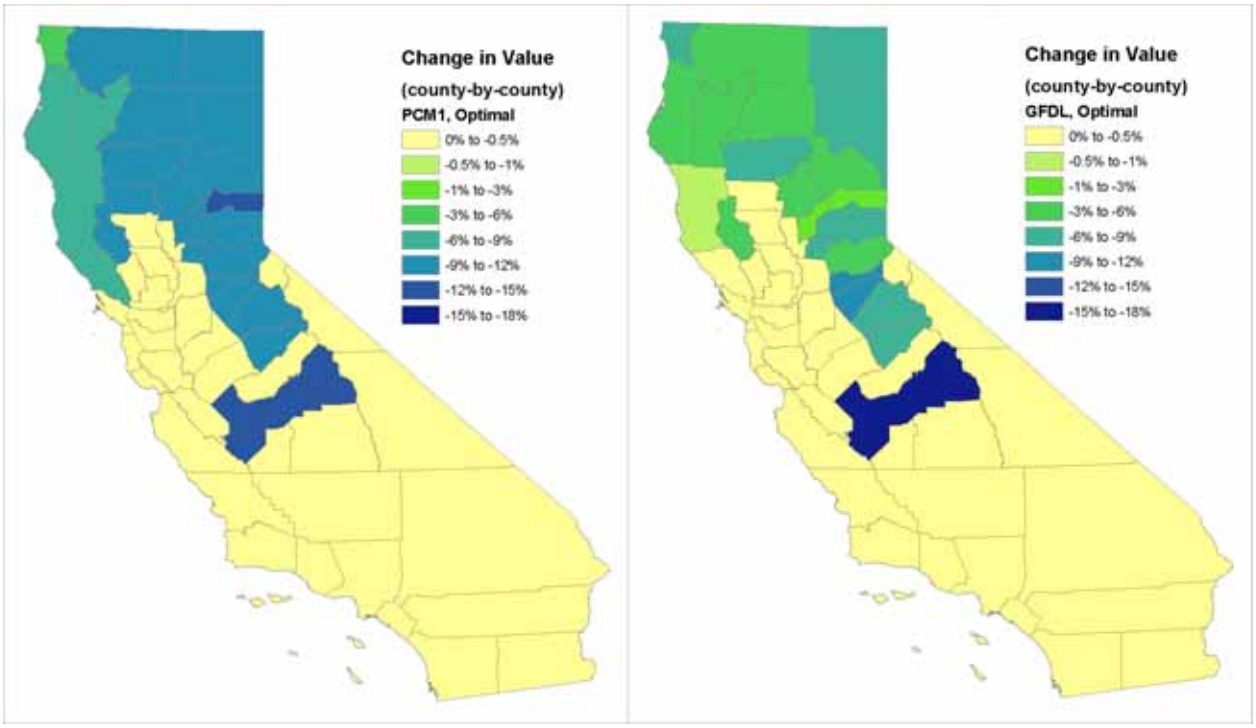


Figure 3.3.1. Proportion of total state loss in value assigned to individual counties

(a) PCM1, climate change price series, A2, optimal management; (b) GFDL, climate change price series, A2, optimal management

Figure 3.3.2 shows the percent changes in value within each county as a percentage of the county production. The spatial pattern of value declines by county follows the general pattern of value declines at the grid-cell level (Figure 3.2.1), with the PCM1 climate producing larger, more consistent declines across the state than the GFDL climate. The decreases in the most prolific timber-producing counties are around 6%–7% under the PCM1 climate projection and around 1%–8% under the GFDL climate projection. Among the 24 counties projected to have some change in value, the average decrease is 10.4% for the PCM1 climate and 5.9% for the GFDL climate.



(a) (b)

Figure 3.3.2. Proportional loss in value by county

(a) PCM1, climate change price series, A2, optimal management; (b) GFDL, climate change price series, A2, optimal management. Note that extreme values in Fresno and Madera counties reflect very small sample sizes (<10 sites per county).

Figure 3.3.2 displays the proportion of state loss attributable to individual counties (for the optimal management option). Patterns under other management options were similar, but less pronounced). The greatest proportion of total loss occurs in Mendocino and Humboldt counties, which corresponds to the large proportion of total timber value arising in these counties. Most timber producing counties experience losses of around 5%–10% with proportion of state loss ranging from under 1%–38% (Humboldt) across climate change scenarios.

While the percent change in timber value within the high timber production counties is smaller than in other counties (some of which experience declines greater than 12%), they contain a large portion of the total value for the state. For instance, the decline of 6% in Humboldt County's timber value under the GFDL climate comprises 38% of the total decline in value statewide.

Sierra counties ranked in the top ten for highest percent raw declines, while Humboldt county dominated percent of statewide decline, in both scenarios. Humboldt county ranked twenty-second (PCM1) and fourteenth (GFDL) in decline as percentage of county total but ranked first in percentage of state total in both scenarios. Shasta and Modoc counties ranked in the top ten for both raw decline and proportion of state total.

Some patterns of loss as a function of climate change scenario are apparent. However, the ranking of losses from each climate change scenario is not preserved across counties. For example, in Del Norte County, the largest loss arises from GFDL, whereas in Mendocino County the largest loss arises from PCM1. In general, losses are slightly greater in the PCM1 scenario, owing to its more muted biological gains being swamped by price effects.

3.4. Effects of Management Options

In this section, we calculate the degree to which adaptation can mitigate the negative effects of climate change. Because we do not know precisely how private foresters will react to, or anticipate, climate change, we analyzed our model under a range of management assumptions, as described in the Methods section. Our economic analysis is underpinned by a biogeographic model which predicts, under any given climate change scenario, the suitability over time of each of our 791 sites for growing each of four different classes of species. In other words, the model predicts how quickly each species will grow depending on where it is located, its age, and calendar time (which relates to the climate change scenario). In principle, a forester responsible for optimizing profit on a given parcel of land may choose to alter the rotation interval, the species composition, or both, as a temporal response to climate change.

We assume that private foresters may make different use of this complex array of information, ranging from completely unresponsive (we call this “Naïve”) to a fully optimizing case in which adaptation occurs in anticipation of climate change effects. Recall that our three management scenarios are as follows:

Management Scenario 1: “Naïve.” Under the Naïve scenario, managers are assumed to follow the same rotation interval, and maintain the same species composition, as was optimal prior to any effects of climate change. This approach will not return maximal profits, and it may exaggerate the effects of climate change, since no adaptation is allowed to occur.

Management Scenario 2: “Rotation.” Under the Rotation scenario, managers acknowledge that the ecosystem, and thus the biological productivity of their land is changing. In response, they alter the rotation interval. For example, if on a given parcel Ponderosa Pine are expected to grow more rapidly early on, and then slow their growth at an earlier age, a forester following the Rotation management assumption may choose to harvest at a younger age. The optimal age of harvest is determined within the model for every parcel and every time period.

Management Scenario 3: “Optimal.” The Optimal management scenario provides an upper bound on the potential adaptation to climate change. Taken literally, this scenario assumes foresters can perfectly anticipate the effects of climate change on their parcel of land, and fully internalize that information into both their rotation and species composition decisions. For example, a given climate change scenario may forecast a dramatic shift in 2015 of productivity of a given parcel. Under the Optimal management scenario, we assume the forester anticipates this shift and acts optimally with that information (e.g., by harvesting the current species in 2014, even though its typical rotation interval has not been achieved, and replanting a different species that will more fully capitalize in the change in productivity).

By definition, the present value of a forested parcel is highest under the Optimal scenario, second highest under the Rotation scenario, and lowest under the Naïve scenario. Our interest here is in calculating the degree to which anticipating the effects of climate change (which we will interpret here as adaptation), and adjusting behavior accordingly, can mitigate the negative effects of climate change.

To perform those calculations, we ran our full model separately under each of the three management scenarios described above. We saved the present value of timberlands in each of the 791 sites and aggregated to the county level, as in Section 3.3. The results are summarized in three maps, provided as Figure 3.4.1a–c.

Figure 3.4.1a shows the percentage change in value from moving from the “Naïve” management scenario to the “Rotation” management scenario. In other words, it displays the benefit of allowing foresters to optimally adjust the rotation interval, but not the species composition, on their parcels. While there is some spatial variability in these results, the key finding here is that the gains from allowing adjustments in rotation interval are relatively small. The maximum benefit is around 4%, and occurs mainly in the Sierra.

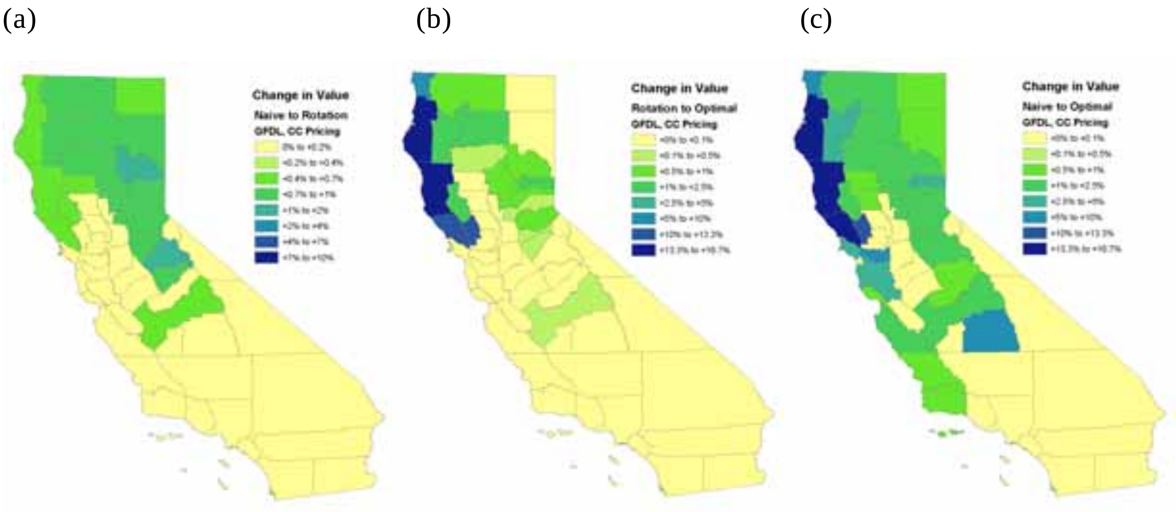


Figure 3.4.1. Percentage change in value from the management option

(a) Naïve to rotation; (b) Rotation to optimal; and (c) Naïve to optimal. All results are from using the GFDL model, climate price series, and A2 emissions scenario.

Figure 3.4.1b shows the percentage change in value from moving from the “Rotation” management scenario to the “Optimal” management scenario. This can be interpreted as the percentage gain in value from allowing foresters to also adjust species composition on their parcel. Because the effects of climate change on productivity can be significant, it turns out that altering species composition on certain parcels over time will enhance the value of forestry on those parcels quite substantially. The benefits of allowing this type of adaptation can be as large as 10%–15%, primarily in the north coastal counties, where Redwood is a viable, and valuable, commercial species.

Finally, Figure 3.4.3c shows the total percentage change in value from the “Naïve” scenario to the “Optimal” scenario. This sums up all previously described changes and illustrates that adaptation can have significant effects on the value of forested lands in many of California’s counties.

3.5. Economic Impact of a Carbon Market

While our overall objective was to estimate the spatial and aggregate economic effects of climate change to California's private forestlands, we had a secondary objective to investigate the impact of a carbon market on those effects. To do so, we modeled the total carbon sequestered on any given parcel, as a function of the growth parameters (driven by our biological model, coupled with the climate change prediction). We then introduced a hypothetical carbon market in which landowners could receive a payment for each ton of carbon sequestered in a given year (details given in the Methods section). Previous research has shown that the presence of such a carbon market could incentivize landowners to alter the rotation interval (it turns out this can either increase or decrease), the species mix (e.g., to switch to more efficient carbon sequestering species), or both.

Adding a carbon market to our already complex dynamic optimization problem is an arduous task. But by doing so, we are able to produce estimates of how landowners will optimally respond to the presence of a carbon market. In particular, we are interested in how they trade off between optimizing actions to achieve a large carbon payment versus optimizing actions to achieve a high profit from their forestry venture. Ultimately, though, we are interested in the economic impact of climate change on any given parcel, with and without the carbon market. The difference between these two provides an estimate of the degree to which the presence of the carbon market can mitigate the economic impacts of climate change. For example, consider the effects of climate change on a particular tract of land. Suppose climate change causes a 15% decline in value without a carbon market, but only a 12% decline in value with a carbon market. In this case, the presence of the carbon market mitigated the negative consequences of climate change. On the other hand, if the decline had been 17% with a carbon market, then the presence of the carbon market acted to increase the negative consequences of climate change.

We have run the full suite of analyses for California, and we display the results in Figures 3.5.1–3.5.3. Figures 3.5.1 and 3.5.2 display the economic impacts of climate change with and without a carbon market, respectively, using the GFDL, A2 climate change scenario. The figures show that the spatial distribution of economic impact of climate change is similar, though with different magnitudes, when we introduce a carbon market (Figure 3.5.2).

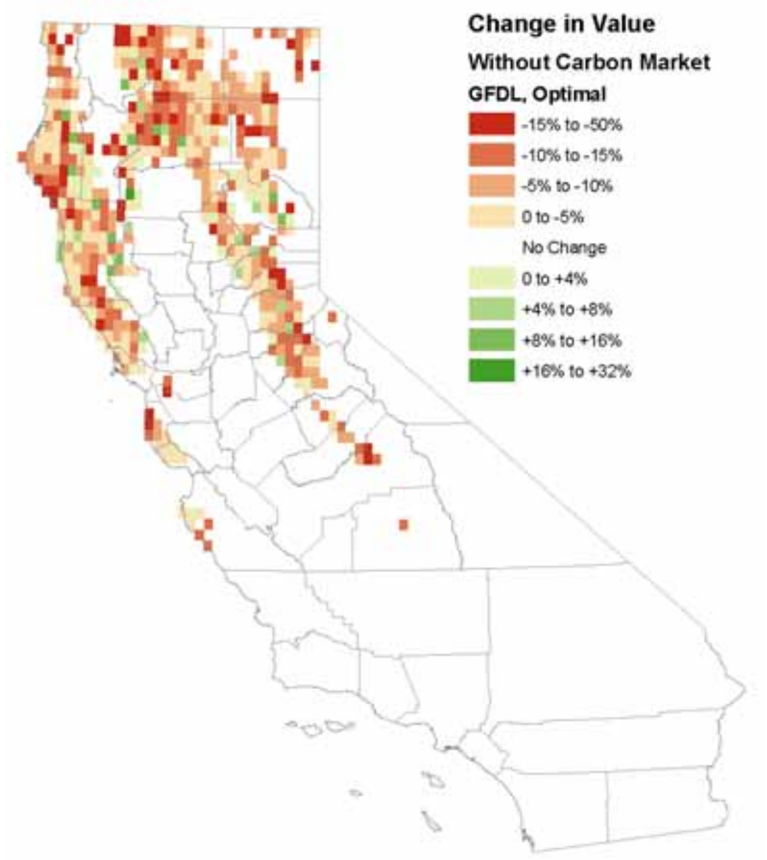


Figure 3.5.1. Percentage change in value under non-carbon pricing

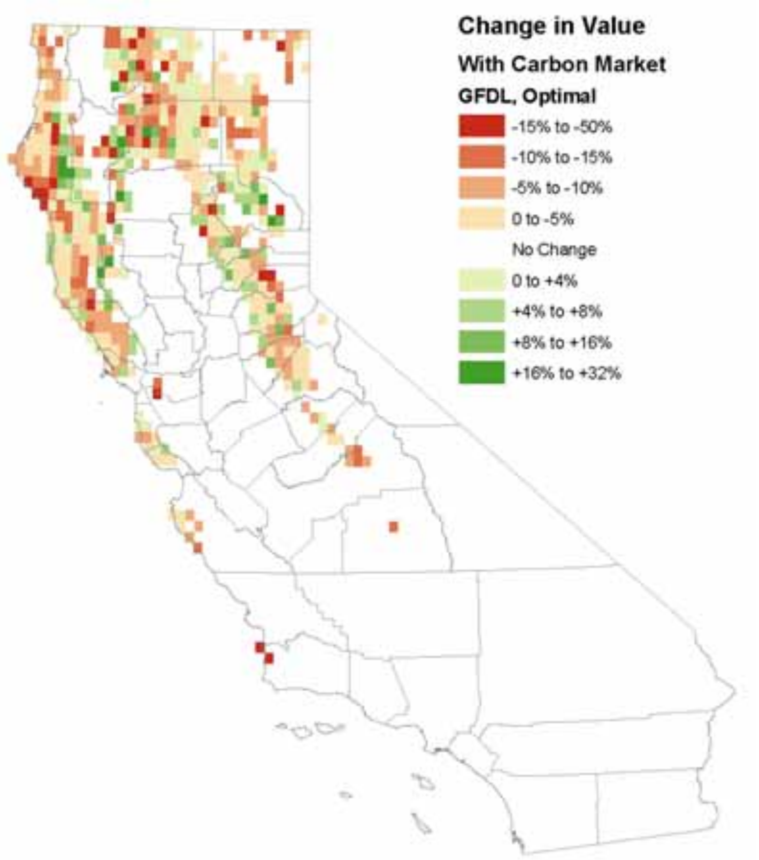


Figure 3.5.2. Percentage change in value under carbon pricing

The difference between the maps, Figure 3.5.3, more clearly depicts this result. The key finding from this figure is that the presence of a carbon market lessens the impact of climate change in all locations, but this effect is stronger in some areas than in others. The effect of the carbon market is greatest in the Sierra and least in Mendocino and Humboldt, where timber values are high. This has important implications for land use change, as will be discussed in the following section.

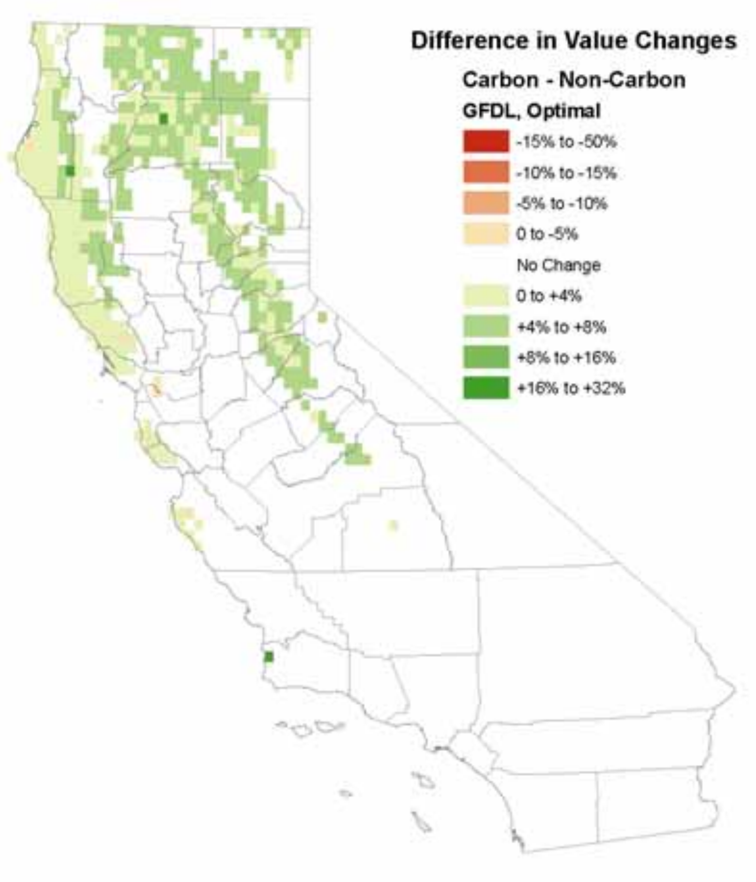


Figure 3.5.3. Difference in value changes from non-carbon to carbon pricing

3.6. Implications for Land Use and Policy

Land use change is driven by economic value and other factors, making economics of land use central in the effectiveness of policies to influence or maintain certain land uses. The results of this study are directly applicable in assessing possible land use changes and in considering where policy intervention may be desirable to maintain working timberland or forested landscapes.

Timberland in California is under increasing pressure from residential development (ex-urban growth) and in some cases, agriculture. Declines in the value of timberlands can act to accentuate trends towards development of timberland or conversion to agriculture.

Our results indicate that climate change could influence these trends. Decreasing timber value across much of the state can predispose lands to conversion to higher value uses. The loss of timberland value will come at a time when other uses are likely to be increasing in value—a confluence of trends that has already resulted in decrease in timber harvest and loss of timberlands. Climate change therefore provides more reason to consider policy interventions where these conversions to other land uses are undesirable.

Intersection of high values for residential use and decreasing timber value raises the likelihood of conversion of timberland. Figure 3.6.1 shows that there is high correspondence of land with decreasing timber value and projected 2050–2080 residential growth. Areas of coincidence are particularly noteworthy in the Sonoma-Mendocino wine country and in the Sierra foothills, two areas in which market dynamics are already favoring non-forest land uses.

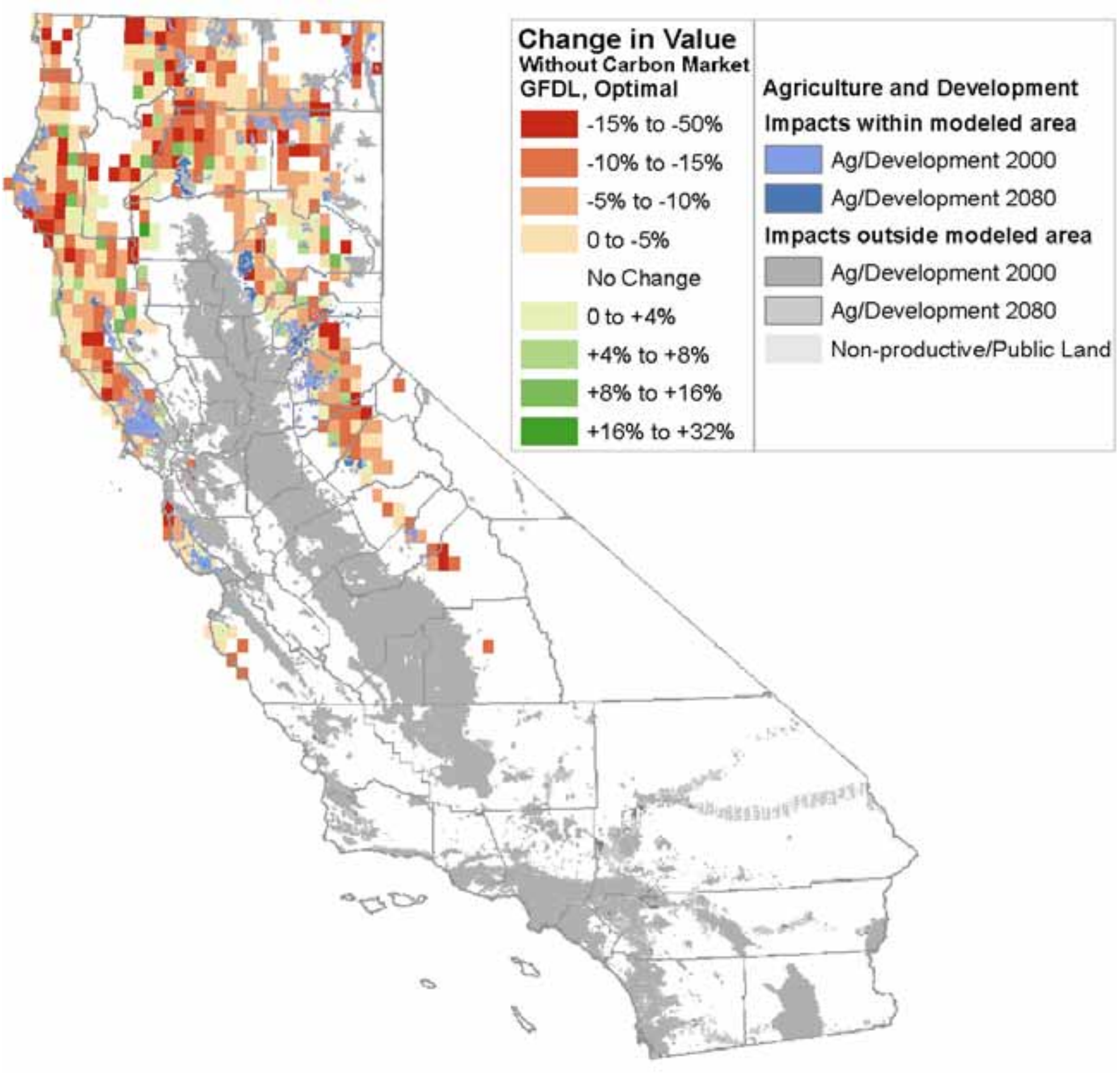


Figure 3.6.1. Overlay of agriculture and development impacts with projected changes in timber value for the GFDL A2 climate scenario. Outputs from the CURBA urban growth model are combined with agricultural land classifications from GAP data. Areas of existing impact are shown here in light blue and dark gray, while expanding of impacts into new areas are shown in dark blue and medium gray.

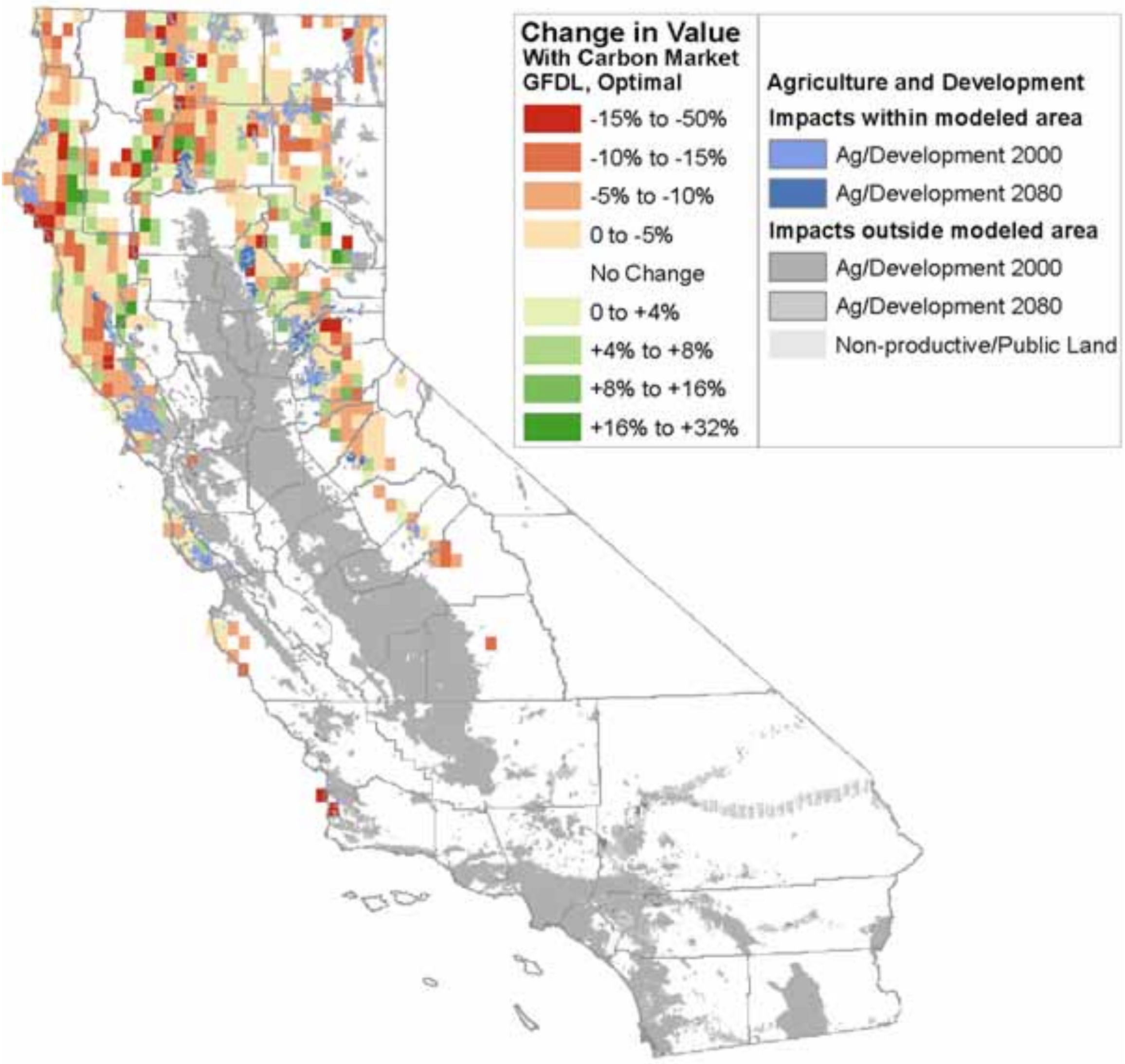


Figure 3.6.2. Overlay of agriculture and development impacts with projected changes in timber value for the GFDL climate scenario - with carbon income. (Note reduced coincidence of urban expansion with areas of strongly declining timber value relative to Figure 3.6.1.)

The private lands that are the focus of this study will be under increasing pressure for development and conversion, and climate change will greatly intensify this pressure in some key regions. Development corridors leading outward from the Sacramento and San Francisco Bay regions show strong overlap of declining timber values, driven by range retreats of high-value species under climate change, with expanding residential and ex-urban development, fueled by demographics and growth in housing need.

Strongly declining timber values in the two high-growth areas, Sonoma-Mendocino and Nevada-Placer-El Dorado in the Sierra foothills indicate that privately held timberland in these areas may undergo more rapid conversion due to climate change. These are two areas with already high rates of land use change.

Other areas of the state, including Southern California and the Santa Cruz mountains, may see pressure to convert timberland outpace income. While timber value change in Southern California is modest, it builds on a low base in a setting where development pressure is intense. It seems likely that there will be heavy conversion of private timberland in this region absent policy intervention. In the Santa Cruz mountains, the overlap of declines and project development less coincident, but value declines are more pronounced, making loss of timberlands a concern under climate change in this region as well.

Absent non-market reasons, the conversion or loss of timberlands is not in itself cause for concern. Land finding its highest value use occurs seamlessly in the marketplace and pays economic dividends. However, loss of timberland may be associated with loss of values that may not be well-represented in markets. Recreation value, climate change reduction, and watershed protection are examples. While markets for climate change services (carbon markets under California law or international voluntary markets) may soon exist, several other ecosystem services of forests may remain poorly represented in markets, making policy intervention to preserve these contributions of forest a consideration.

Carbon income (Figure 3.6.2) lessens value declines in areas at risk of development, such as the Sierra corridor east of Sacramento and some areas of Mendocino and Humboldt counties. In other locations, including some within these generally improving zones, value declines remain substantial in areas with strongly competing future urban land use, indicating that other policy measures would be needed to complement carbon revenue in some sites if conversion of timberland is to be avoided.

Policy tools favoring retention of timberlands might include market-based solutions, tax relief or incentives for smallholders, purchase programs for lands of high conservation or recreation value, or actions that would draw development to other areas. Policy tools lessening the impact of climate change on land use conversion include institution of carbon markets and funding adaptation of timber management to climate change. Carbon markets help generate income in areas suffering the greatest timber value declines, thereby providing incentive to keep land in forest. Adaptation programs can help reduce the impact of climate change on value, again favoring retention of timberland. Without some individual or combination of these policy tools, it seems likely that climate change will hasten conversion of timberlands in some of the most affected regions of the state.

3.7. Statewide Effects of Climate Change

Thus far, our results have been presented either as disaggregated spatial units (791 sites covering all private forest lands in California) or as aggregated county-level results. To obtain our final result, the economic impact of climate change to California’s timberlands, we aggregate still further to the state level. Below we display three sets of results, each corresponding to a different time frame over which change may occur. Each table contains four rows, each corresponding to a different climate change / price scenario, and three columns, each corresponding to a different management scenario. The entries in the cells provide our overall estimate of the statewide percentage impact of climate change on California’s private forestlands, under the given price series, climate change scenario, and management scenario combination. A2 emissions scenario results are given first, followed by findings for the B1 analyses. By 2080 changes are similar in A2 and B1 scenarios, but 2020 and 2050 values are markedly different.

Tables 3.7.1–3.7.3 show the percentage change in statewide timber value for three different years under the A2 scenario.

Table 3.7.1. Percentage change in statewide timber value, 2080 A2; under multiple climate, pricing, and management assumptions

Climate Scenario	Price Series	Management Scenario		
		Naïve	Rotation	Optimal
PCM1	Baseline	+1.5%	+1.6%	+1.8%
	Climate Change	-8.5%	-8.1%	-8.1%
GFDL	Baseline	+5.6%	+5.7%	+5.3%
	Climate Change	-4.7%	-4.4%	-4.9%

Table 3.7.2. Percentage change in statewide timber value, 2050 A2; under multiple climate, pricing, and management assumptions

Climate Scenario	Price Series	Management Scenario		
		Naïve	Rotation	Optimal
PCM1	Baseline	+1.4%	+1.4%	+1.5%
	Climate Change	-3.6%	-3.4%	-3.3%
GFDL	Baseline	+5.4%	+5.5%	+4.9%
	Climate Change	+0.4%	+0.5%	0.0%

Table 3.7.3. Percentage change in statewide timber value, 2020 A2; under multiple climate, pricing, and management assumptions

Climate Scenario	Price Series	Management Scenario		
		Naïve	Rotation	Optimal
PCM1	Baseline	+1.5%	+1.5%	+1.7%
	Climate Change	-3.5%	-3.3%	-3.2%
GFDL	Baseline	+5.6%	+5.7%	+5.3%
	Climate Change	+0.5%	+0.6%	+0.2%

The price series assume that prices will increase in the future, either with or without climate change, but that the climate change price series rises at a significantly slower rate than does the non-climate change price series. This is due to rising productivity attributable to warmer temperatures and more precipitation across the globe, increasing timber supply and thus depressing price. Our findings of enhanced productivity for California timberlands bears out this price expectation—if productivity rises even more at higher latitudes, as it should, global timber prices are likely to fall.

Translating these percentage changes into dollar gains or losses requires assumptions about discount rates. Because society may value benefits to future generations as much as present benefits, a zero discount rate is often applied in assessing the economic impact of climate change. Following that convention, gains or losses in dollar amounts are presented in tables 3.7.4–3.7.6. By 2080 (Table 3.7.4) dollar changes range from a loss of over $8.1 billion to an increase of $5.4 billion in A2 scenarios, depending on GCM, management, and price scenario. Under A2 scenarios in which price responds to climate change as expected, the dollar changes are always negative by 2080, ranging from -4.2 billion under the GFDL projection and rotation management option to nearly $8.1 billion under the PCM1 projection and naïve management option.

Table 3.7.4. Change in net present value of statewide timber revenues under different climate and management scenarios for climate change – 2080 A2 (0% discount rate)

Climate Scenario	Price Series	Management Scenario		
		Naïve	Rotation	Optimal
PCM1	Baseline	+$1,442,518,370	+$1,492,411,390	+$1,685,174,490
	Climate Change	-$8,056,701,190	-$7,719,775,980	-$7,674,566,580
GFDL	Baseline	+$5,356,187,350	+$5,385,982,390	+$5,021,752,270
	Climate Change	-$4,469,834,370	-$4,212,168,310	-$4,651,767,370

Table 3.7.5. Change in net present value of statewide timber revenues under different climate and management scenarios for climate change – 2050 A2 (0% discount rate)

Climate Scenario	Price Series	Management Scenario		
		Naïve	Rotation	Optimal
PCM1	Baseline	+$1,309,696,790	+$1,355,604,130	+$1,432,514,870
	Climate Change	-$3,386,783,160	-$3,200,220,890	-$3,137,132,820
GFDL	Baseline	+$5,143,826,070	+$5,174,241,910	+$4,657,683,010
	Climate Change	+$348,555,990	+$481,863,720	+$16,268,980

Table 3.7.6. Change in net present value of statewide timber revenues under different climate and management scenarios for climate change – 2020 A2 (0% discount rate)

Climate Scenario	Price Series	Management Scenario		
		Naïve	Rotation	Optimal
PCM1	Baseline	+$1,391,954,060	+$1,440,890,840	+$1,617,564,390
	Climate Change	-$3,326,608,530	-$3,132,537,550	-$3,019,951,660
GFDL	Baseline	+$5,341,258,680	+$5,370,166,490	+$4,999,263,940
	Climate Change	+$437,596,410	+$581,404,330	+$177,019,490

Climate change has two main effects on value. First, it affects productivity, as described above. Second, it reduces the prices of timber, relative to the prices that would have been achieved in the absence of climate change. Under the climate change price series, we find fairly substantial negative impacts of climate change under all climate change scenarios and under all management scenarios. Under this price series, we project impacts ranging from 4.9% losses to 8.5% losses by the end of the century under the A2 emissions scenario, depending on GCM and management assumptions.

The "baseline" price series assumes that climate change has no effect on timber prices. Under this scenario, timber prices rise through time in a way that is independent of the climate change scenario. Under that assumption, the projected losses are reversed and small gains are seen in all scenarios—increases of between 1.5% and 5.7% by the end of the century in the A2 scenario.

There is a strong temporal discontinuity in the GFDL A2 climate change scenario. This scenario shows mild positive increases in value in early- to mid-century, changing to a pronounced negative change by the end of the century. This discontinuity holds in all management options for this scenario. There are no other strong temporal discontinuities in these findings. Gains and losses both remain relatively constant or build gradually throughout the century for other scenarios.

The interplay between price and productivity is seen clearly in the differences in value change between A2 and B1 emissions scenarios (compare Tables 3.7.1–3.7.3 with Tables 3.7.7–3.7.9). In the B1 scenario, emissions are lower, resulting in less warming. This in turn leads to lower increases in productivity in California. There is no estimate for global timber prices under a B1 scenario, but prices will be closer to baseline. Under baseline prices, there is gain in value in B1 scenarios due to rising productivity. However, under climate change prices, losses are seen due to a strong price decline swamping the productivity increase.

Table 3.7.7. Percentage change in statewide timber value – 2080, B1; under multiple climate, price, and management assumptions

Climate Scenario	Price Series	Management Scenario		
		Naïve	Rotation	Optimal
PCM1	Baseline	+1.4%	+1.4%	+1.8%
	Climate Change	-8.7%	-8.3%	-8.1%
GFDL	Baseline	+2.3%	+2.3%	+2.2%
	Climate Change	-7.8%	-7.5%	-7.8%

Table 3.7.8. Percentage change in statewide timber value – 2050, B1; under multiple climate, price, and management assumptions

Climate Scenario	Price Series	Management Scenario		
		Naïve	Rotation	Optimal
PCM1	Baseline	+1.4%	+1.4%	+1.8%
	Climate Change	-8.7%	-8.3%	-8.1%
GFDL	Baseline	+2.3%	+2.3%	+2.1%
	Climate Change	-7.8%	-7.5%	-7.8%

Table 3.7.9. Percentage change in statewide timber value – 2020, B1; under multiple climate, price and management assumptions

Climate Scenario	Price Series	Management Scenario		
		Naïve	Rotation	Optimal
PCM1	Baseline	+1.3%	+1.3%	+1.6%
	Climate Change	-8.7%	-8.4%	-8.2%
GFDL	Baseline	+2.1%	+2.1%	+1.9%
	Climate Change	-7.9%	-7.7%	-7.9%

Our baseline price series (see Tables 3.7.10–3.7.12) overestimates gains under the B1 scenario because productivity will still rise under this scenario, driving down global timber prices. The climate change price series overestimates losses, however, because it is based on studies using the A2 scenario in which productivity increase (and therefore price decline) will be more pronounced than in a B1 scenario. More accurate estimation of value change under B1 scenarios awaits studies of global timber price changes under this scenario. However, note that since current emissions already exceed even A2 scenarios, these low emissions B1 scenarios may not be realistic. The prospect for global price studies using this scenario may therefore be limited.

Table 3.7.10. Change in net present value of statewide timber revenues under different climate and management scenarios for climate change – 2080 B1 (0% discount rate)

Climate Scenario	Price Series	Management Scenario		
		Naïve	Rotation	Optimal
PCM1	Baseline	+$1,289,346,010	+$1,337,482,250	+$1,670,100,610
	Climate Change	-$8,213,339,020	-$7,881,187,160	-$7,703,964,490
GFDL	Baseline	+$2,177,945,070	+$2,186,035,260	+$2,044,147,900
	Climate Change	-$7,376,756,340	-$7,143,419,990	-$7,375,121,070

Table 3.7.11. Change in net present value of statewide timber revenues under different climate and management scenarios for climate change – 2050 B1 (0% discount rate)

Climate Scenario	Price Series	Management Scenario		
		Naïve	Rotation	Optimal
PCM1	Baseline	+$1,283,010,950	+$1,328,509,240	+$1,664,365,770
	Climate Change	-$7,763,945,080	-$7,352,091,450	-$7,101,382,980
GFDL	Baseline	+$2,170,727,180	+$2,177,573,390	+$2,033,925,010
	Climate Change	-$6,947,732,630	-$6,645,250,410	-$6,813,198,070

Table 3.7.12. Change in net present value of statewide timber revenues under different climate and management scenarios for climate change – 2020 B1 (0% discount rate)

Climate Scenario	Price Series	Management Scenario		
		Naïve	Rotation	Optimal
PCM1	Baseline	+$1,233,056,620	+$1,278,706,010	+$1,547,604,600
	Climate Change	-$3,514,217,280	-$3,468,026,250	-$3,083,026,790

GFDL	Baseline	+$1,994,143,860	+$2,005,493,540	+$1,840,413,500
	Climate Change	-$2,793,966,430	-$2,778,569,880	-$2,813,401,940

The most important finding across all scenarios is likely negative trends in timberland value associated with relatively lower global timber prices due to climate change. This finding echoes earlier studies of climate change effects on California timber revenues. Perhaps most significant for California policy is the spatial distribution of potential losses, which in some areas will intersect strongly with areas undergoing urban development and other land conversion processes. Policy measures may be warranted to retain timberlands in these areas.

4.0 Summary

Our analysis projects a loss of 4.9%–8.5% of timber harvest value in California due to climate change. The value of California timber is influenced by two key factors that change under climate change: price and production. Production-related changes are dominated by declining values. There is high spatial variability across the state, from strong declines to modest increases. The spatial variability in response is much stronger than the variability between climate scenarios. The warmer, high-emissions scenarios under both GCMs studied show more negative changes in value than do the low emissions (cooler) scenarios.

When price effects are included, declines are accentuated. Large declines are observable in many locations, while increases in value are rare. Many areas show little or no net change in value. Areas of strong decline are seen just inland along the Mendocino coast, in the Santa Cruz mountains, in parts of the Sierra and in the extreme north of the state.

The patterns of decline are determined by interactions of price, productivity, and species range. Locations in which productivity and species mix remain relatively constant are vulnerable to declines due to the relatively lower price resulting from climate change. Areas in which high-value timber species are losing range or productivity show particularly sharp declines. Conversely, areas in which productivity increases and shifts to more valuable species occur, these increases tend to offset the lower price seen with climate change.

These value changes increase the likelihood of strongly patterned changes in land use, such as conversion of timberland to residential use. For instance, areas north of San Francisco and bordering the Central Valley see substantial declines in value in the GFDL scenarios. That will make these areas more vulnerable to conversion to residential use, a trend that is already significant in these parts of the state. This pattern is much less pronounced in the PCM1 scenarios.

Most timber producing counties experience losses of 2%–20% under each climate change scenario, with significant spatial differences. Moving between management scenarios, from the “Rotation” or “Naïve” management scenarios to the “Optimal” management scenario, resulted in increases in value. Moving from “Naïve” management to “Rotation” showed little increase, indicating that manipulating rotation times alone is not a powerful management tool for climate change effects. Because the effects of climate change on productivity can be marked, altering species composition on certain parcels over time will enhance the value of forestry on those parcels quite substantially.

The carbon market can mitigate the economic impacts of climate change. For example, consider the effects of climate change on a particular tract of land. Suppose climate change causes a 15%

decline in value without a carbon market, but only a 12% decline in value with a carbon market. In this case, the presence of the carbon market mitigated the negative consequences of climate change. On the other hand, if the decline had been 17% with a carbon market, then the presence of the carbon market acted to increase the negative consequences of climate change.

The climate change results reported here could clearly influence land use trends. Decreasing timber value across much of the state can predispose lands to conversion to higher value uses. The loss of timberland value will come at a time when other uses are likely to be increasing in value–a confluence of trends that has already resulted in decrease in timber harvest and loss of timberlands. The results of this study are therefore reason to consider policy interventions where these conversions to other land uses are undesirable.

Areas of coincidence are particularly noteworthy in the Sonoma-Mendocino wine country and in the Sierra foothills—areas in which market dynamics are already favoring non-forest land uses. Development corridors leading outward from the Sacramento and San Francisco Bay regions show strong overlap of declining timber values, driven by range retreats of high-value species under climate change, with expanding residential and ex-urban development, fueled by demographics and growth in housing need.

Loss of timberland may be associated with loss of values that may not be well-represented in markets. Recreation value, climate change reduction and watershed protection are examples. While markets for climate change services (carbon markets under California law or international voluntary markets) may soon exist, several other ecosystem services of forests may remain poorly represented in markets, making policy intervention to preserve these contributions of forest a consideration.

Policy tools favoring retention of timberlands might include market-based solutions, tax relief or incentives for smallholders, purchase programs for lands of high conservation or recreation value, or actions that would draw development to other areas. Policy tools lessening the impact of climate change on land use conversion include institution of carbon markets and funding adaptation of timber management to climate change. Carbon markets help generate income in areas suffering the greatest timber value declines (see Section 3.6), thereby providing incentive to keep land in forest. Adaptation programs can help reduce the impact of climate change on value, again favoring retention of timberland. Without some individual or combination of these policy tools, it seems likely that climate change will hasten conversion of timberlands in some of the most impacted regions of the state.

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6.0 Glossary

3-PG	Physiological Principles for Predicting Growth
BIOMOD	a species distribution model
DEM	digital elevation model
EO	economic optimization
FC	forest certification
FIA	forest inventory and analysis
FRAP	Fire and Resource Assessment Program
GCM	General Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory
GIS	geographic information system
IPCC	Intergovernmental Panel on Climate Change
MBF	thousand board feet
PCM1	National Center for Atmospheric Research Parallel Climate Model, version 1
PF	post-fire
STATSGO	State Soil Geographic Database
UIUC	University of Illinois at Urbana-Champaign