THE RESPONSE OF VEGETATION DISTRIBUTION, ECOSYSTEM PRODUCTIVITY, AND FIRE IN CALIFORNIA TO FUTURE CLIMATE SCENARIOS SIMULATED BY THE MC1 DYNAMIC VEGETATION MODEL

WHITE PAPER

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Prepared By:
James M. Lenihan, Dominique Bachelet,
Raymond Drapek, and Ronald P. Neilson

DISCLAIMER

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Preface

The 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, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, the Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and 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.

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Abstract

The objective of this study was to dynamically simulate the response of vegetation distribution, carbon, and fire to three scenarios of future climate change for California using the MAPSS-CENTURY (MC1) dynamic general vegetation model. Under all three scenarios, Alpine/Subalpine Forest cover declined with increased growing season length and warmth, and increases in the productivity of evergreen hardwoods with increased temperature led to the displacement of Evergreen Conifer Forest by Mixed Evergreen Forest. The simulated responses to changes in precipitation were complex, involving not only the effect on vegetation productivity, but also changes in tree-grass competition mediated by fire. Grassland expanded, largely at the expense of Woodland and Shrubland, even under the relatively cool and moist PCM-A2 climate scenario where increased woody plant production was offset by increased wildfire.

Increases in net primary productivity (NPP) under the PCM-A2 climate scenario contributed to a simulated carbon sink of about 321 teragrams (353.8 million tons) for California by the end of the century. Declines in net primary productivity (NPP) under the two warmer and drier GFDL climate scenarios, most evident under the GFDL-A2 scenario, contributed to a net loss of carbon ranging from about 76 to 129 Tg (83.8 to 142.2 million tons) by the end of the century.

Total annual area burned in California increased under all three scenarios, ranging from 9%–15% above the historical norm by the end of the century. Regional variation in the simulated changes in area burned was largely a product of changes in vegetation productivity and shifts in the relative dominance of woody plants and grasses. Annual biomass consumption by fire by the end of the century was about 18% greater than the historical norm under the more productive PCM-A2 scenario. Under the warmer and drier GFDL scenarios, simulated biomass consumption was also greater than normal for the first few decades of the century as drought-stressed woodlands and shrublands burned and were converted to grassland. After this transitional period, lower than normal NPP produced less fuel, and biomass consumed was at, or below, the historical norm by the end of the century under the GFDL scenarios.

Considerable uncertainty exists with respect to regional-scale impacts of global warming on the natural ecosystem of California. Much of this uncertainty resides in the differences among different GCM climate scenarios and assumed trajectories of future greenhouse gas emissions as illustrated in this study. In addition, ecosystem models and their response to projected climate change can always be improved through careful testing and enhancement of model processes. The direct effects of increasing CO_2 on ecosystem productivity and water use, and assumptions regarding fire suppression and the availability of ignition sources, were identified as sources of uncertainty to be addressed through further model testing and development.

1.0 Introduction

California is one of the most climatically and biologically diverse areas in the world. There is more diversity in the state's land forms, climate, ecosystems, and species than in any comparably sized region in the United States (Holland and Keil 1995). This diversity of habitats sustains a greater level of species diversity and endemism than is found in any other region of the nation (Davis et al. 1998). Much of California's biological wealth is threatened by the state's burgeoning population and the consequent impacts on the landscape. Throughout the state, natural habitats have been and continue to be altered and fragmented, endangering the state's biological diversity (Barbour et al. 1993).

In the future, global climate change will increasingly interact with and intensify the pressures of a growing population on the natural ecosystems of California. It is not possible to accurately predict the response of the natural systems to global climate change through direct experimentation. The physical extent, complexity, and expense of even a single-factor experiment for an entire ecosystem is usually prohibitive (Aber et al. 2001). However, analyses of the sensitivity of natural ecosystems to climate change can be made using ecosystem models that integrate information from direct experimentation.

Dynamic global vegetation models (DGVMs) (e.g., Cramer et al. 2001) simulate vegetation distribution at continental to global scales both over the recent past and in response to transient climate change. These models explicitly simulate vegetation dynamics and nutrient cycles, and a very few also simulate the dynamic impacts of disturbance due to fire. One important limitation of most DGVMs is that they often only simulate potential or natural (i.e., unmanaged) vegetation and fail to incorporate the impacts of humans on the environment from activities such as logging, agriculture, and urbanization. Similarly, they do not include the effects of air pollution, such as the deleterious effects of ozone, on vegetation. In some cases, human-induced changes in land cover will greatly affect the response of the vegetation to climate change. Human-dominated ecosystems can serve as barriers and prevent or slow the migration of some species to new regions while, on the other hand, they can allow the spread of exotic species competing with native plants. Moreover, proximity to human centers greatly affects the frequency and nature of the ignition sources for wildfires. Where vegetation cover is more natural and less subject to human impacts, the model projections may be more realistic. Another limitation of the models is that they generally do not include the effects of grazing or the occurrence of diseases by pests or pathogens. It is unclear how climate change will alter the interactions between these other factors and climate, but in some cases, the effects could result in vegetation responses not predicted by the models.

In previous studies, the MC1 DGVM has generated simulations of the response of vegetation distribution, ecosystem productivity, and fire to the observed historical climate and to several scenarios of potential future climate change for California (Lenihan et al. 2003, Hayhoe et al. 2005). The results of the simulations for the historical climate compared favorably to independent estimates and observations. The general response to increasing temperatures under all future climate scenarios was characterized by a shift in dominance from needle-leaved to broad-leaved lifeforms and by increases in vegetation productivity, especially in the relatively cool and mesic regions of the state. The simulated responses to changes in precipitation were complex, involving not only the effect on vegetation productivity, but also changes in tree-grass competition mediated by fire. The increasing trends in simulated fire area under all scenarios were primarily a response to changes in vegetation biomass. In the present study, MC1 simulations were generated under three new future climate scenarios for California.

2.0 Methods

2.1. The Model

MC1 is a dynamic global vegetation model (DGVM) that simulates plant type mixtures and vegetation types; the movement of carbon, nitrogen, and water through ecosystems; and fire disturbance. MC1 routinely generates simulations tens to hundreds of years long on spatial data grids with cell sizes ranging from 900 m^2 (900 square meters, equivalent to 9688 square feet) to about 2500 km^2 (2500 square kilometers, equivalent to 965 square miles) (Daly et al. 2000; Bachelet et al. 2000, 2001b; Aber et al. 2001; Lenihan et al. 2003). Grid cell size for the simulations described in this report was 100 km^2 (38.6 square miles). The model reads climate data for each month in a simulation, and calls interacting modules that simulate biogeography, biogeochemistry, and fire disturbance.

2.1.1. Biogeography module

The biogeography module simulates changes in the mixture of different types of trees, shrubs, and grasses in each grid cell over time as a response to climate and fire. Woody plants are represented in the model as trees and shrubs, and as different lifeforms distinguished by leaf characteristics. The three tree and shrub lifeforms represented in the model are evergreen needleleaf, evergreen broadleaf, and deciduous broadleaf. The two types of grass lifeforms represented in the model are distinguished by their response to temperature. The C3 grass lifeform is most productive in relatively cool habitats, while C4 grasses are more tolerant of higher temperatures.

The biogeography module simulates the mixture of plant lifeforms in each grid cell each year. Woody plants in the mixture are determined to be either trees or shrubs (not both) based on the current amount of woody plant biomass simulated by the biogeochemistry module (see Section 2.1.2). The relative proportion of different tree or shrub lifeforms in the simulated mixture is determined by the temperature of the coldest month and the amount of precipitation during the growing season. A relatively large proportion of evergreen needleleaf trees or shrubs make up the mixture when the temperature of the coldest month is relatively low. When the temperature of the coldest month is relatively high, a greater proportion of the mixture is made up of evergreen broadleaf trees or shrubs. Deciduous broadleaf trees or shrubs comprise a relatively large proportion of the woody plant mixture when a relatively large amount of the annual precipitation occurs during the growing season. The relative proportion of C3 and C4 grasses in the simulated plant mixture is determined by estimating the potential productivity of each grass lifeform as function of soil temperature during the three warmest consecutive months (Parton et al. 1987).

The simulated plant lifeform mixture together with woody plant and grass biomass simulated by the biogeochemistry module are used by the biogeography module to determine the vegetation type that occurs at each grid cell each year. Of the twenty-two possible vegetation types predicted by the biogeography module, twelve occurred in the simulations for California.

These types were aggregated into seven vegetation classes to simplify the visualization of results. The aggregation scheme and lists of typical regional examples in each vegetation class are listed in Table 1.

Table 1. MC1 vegetation type aggregation scheme and regional examples of the vegetation classes

MC1 Vegetation Class	*MC1 Vegetation Type*	*Regional Examples*
Alpine/Subalpine Forest	Tundra Boreal Forest	Alpine Meadows Lodgepole Pine Forest Whitebark Pine Forest
Evergreen Conifer Forest	Maritime Temperate Conifer Forest Continental Temperate Coniferous Forest	Coastal Redwood Forest Coastal Closed-Cone Pine Forest Mixed Conifer Forest Ponderosa Pine Forest
Mixed Evergreen Forest	Warm Temperate/Subtropical Mixed Forest	Douglas Fir–Tanoak Forest Tanoak–Madrone–Oak Forest Ponderosa Pine–Blackoak Forest
Mixed Evergreen Woodland	Temperate Mixed Xeromorphic Woodland Temperate Conifer Xeromorphic Woodland	Blue Oak Woodland Canyon Live Oak Woodland Northern Juniper Woodland
Grassland	C3 Grassland C4 Grassland	Valley Grassland Southern Coastal Grassland Desert Grassland
Shrubland	Mediterranean Shrubland Temperate Arid Shrubland	Chamise Chaparral Southern Coastal Scrub Sagebrush Steppe
Desert	Subtropical Arid Shrubland	Creosote Brush Scrub Saltbrush Scrub Joshua Tree Woodland

2.1.2. Biogeochemistry module

The biogeochemistry module is a modified version of the CENTURY model (Parton et al. 1994) which simulates plant growth, organic matter decomposition, and the movement of water and nutrients through the ecosystem. Plant growth is limited by temperature, effective moisture (i.e., the balance between the supply of moisture in the soil and the demand for moisture by plants and evaporation), and nutrient availability. In this study, plant growth was assumed not to be limited by nutrient availability. The simulated effect of an increase in atmospheric carbon dioxide (CO_2) is to both increase the rate of plant growth and reduce the demand of plants for moisture. Grasses compete with woody plants (trees or shrubs) for soil moisture in the upper soil layers where both are rooted, while the deeper-rooted woody plants have sole access to moisture in deeper layers. The growth of grass may be limited by reduced light levels in the shade cast by woody plants. The values of variables in the model that control woody plant and grass growth are adjusted based on the plant mixture determined each year by the biogeography module.

2.1.3. Fire disturbance module

The MC1 fire module simulates the occurrence, behavior, and effects of fire. The module simulates the behavior of a simulated fire event in terms of the potential rate of fire spread (Rothermel 1972), the rate at which heat is released along the flaming fire front (fireline intensity, Byram 1959), and the transition from burning only at ground level to also burning in the tree or shrub canopy (van Wagner 1993). Several measurements of the fuel bed are required for simulating fire behavior, and they are estimated by the fire module using information provided by the other two MC1 modules. The current lifeform mixture (provided by the biogeography module) is used by the fire module to select factors that apportion live and dead biomass (provided by the biogeochemical module) into different classes of live and dead fuels. The moisture content of the two live fuel classes (grasses and leaves/twigs of woody plants) are estimated from moisture at different depths in the soil provided by the biogeochemical module. Dead fuel moisture content is estimated from climatic inputs to MC1 (temperature, precipitation, and relative humidity) using different functions for each of the three dead fuel size-classes.

Fire events are triggered in the model when the moisture content of the largest dead fuel class and the simulated rate of fire spread meet set thresholds. Sources of ignition (e.g., lightning or anthropogenic) are assumed to be always available. The fire occurrence thresholds were calibrated to limit the occurrence of simulated fires to only the most extreme events. Large and severe fires account for a very large fraction of the annual area burned historically (Strauss et al. 1989). These events are also likely to be least constrained by heterogeneities in topography and fuel moisture and loading that are poorly represented by relatively coarse-scale input data grids (Turner and Romme 1994). Topography and fuels are assumed to be uniform within each grid cell, and there is no cell-to-cell interaction in the model, so area burned is not simulated explicitly as fire spread within a given cell, or from one cell to another. Instead, the fraction of a cell burned by a fire event is estimated as a linear function of the time since the last fire event with an adjustment made for the potential rate of fire spread. The MC1 fire module generates a trend in total area burned over the historical period that is within the limits of an independently estimated range of variability for the natural (i.e., pre-settlement) fire regime in California (Lenihan et al. 2003). Fire suppression was not simulated by the fire module in this study.

The direct effects of fire simulated by the fire module are the consumption and mortality of dead and live vegetation carbon, which is removed from (or transferred to) the appropriate carbon pools in the biogeochemistry module. Live carbon mortality and consumption are simulated using functions (Peterson and Ryan 1986) of fireline intensity and the tree canopy structure (i.e., crown height, crown length, and bark thickness) Dead biomass consumption is simulated using functions of fuel moisture that are fuel-class specific (Peterson and Ryan 1986).

Fire effects extend beyond the direct impact on carbon and nutrient pools to more indirect and complex effects on tree vs. grass competition. Fire tends to tip the competitive balance towards grasses in the model because much, or all, of the grass biomass consumed regrows in the year following a fire event. Woody biomass consumed or killed is more gradually replaced. A greater competitive advantage over trees promotes greater grass biomass, which, in turn, produces higher fine fuel loadings and changes in the fuel bed structure that promote greater rates of spread and thus more extensive fire.

2.2. The Climate Data

The climate data used as input to the model in this study consisted of monthly time series for all the necessary variables (i.e., precipitation, minimum and maximum temperature, and vapor pressure) distributed on a 100 km^2 (38.6 mi^2) resolution data grid for the state of California. Spatially distributed monthly time-series data for historical (1895–2003) precipitation, temperature, and vapor pressure already existed at a 100 km^2 resolution. This dataset was developed from a subset of climate data generated by the VEMAP model (Vegetation-Ecosystem Modeling and Analysis Project; Kittel et al. 2004) and from observed California station data interpolated to the data grid by PRISM (Parameter-Elevation Regression on Independent Slopes Model; Daly et al. 1994).

To construct spatially distributed climate time-series datasets for the potential future climatic periods (2004–2100) of our simulations, we used coarse-scale monthly output generated by two general circulation models (GCMs)—the Geophysical Fluid Dynamics Laboratory (GFDL) model and the National Center for Atmospheric Research (NCAR) parallel climate model (PCM). Both are state-of-the-art GCMs that include the influence of dynamic oceans and aerosol forcing on the atmosphere. Both GCM models were run from the 1800s to 1995 using observed increases in greenhouse gas concentrations, and into the future using two different emission scenarios described in the *Special Report on Emissions Scenarios* by the Intergovernmental Panel on Climate Change (2000). The A2 high-emissions scenario corresponds to a CO_2 concentration by the end of the century more than three times the pre-industrial level, while the B1 low-emissions scenario results in a doubling of pre-industrial CO_2.

Sufficient climatic inputs for MC1 simulations were available from only three of the GCM–emission scenario experiments (i.e., GFDL-A2, GFDL-B1, and PCM-A2). The GFDL-A2 model run had the greatest increase in temperature (> 4°C or 7.2°F) and was the driest of the three scenarios used here. This scenario was at the high end of temperature changes over California compared to an ensemble of IPCC AR4 model simulations (Cayan et al. 2006). The GFDL-B1 and PCM-A2 runs represented neutral to moderately dry scenarios respectively, with intermediate temperature increases (< 3°C, or 5.4°F) over California.

Using a methodology that is an accepted norm for creating higher-resolution climate scenarios for impact studies, we downscaled the four coarse-scale GCM scenarios to the 100 km^2 resolution (10 x 10 km; 38.6 mi^2). The steps in the development of the scenarios were as follows:

- For each climate variable, monthly averages were calculated for the 1961–1990 GCM-simulated climate for each coarse-scale GCM grid cell over California.
- At each GCM grid cell and for each future simulation month, "deltas" were calculated between the long-term average for each variable (from step 1) and the value for the "target" month taken from the GCM-simulated time series (deltas were calculated as differences for temperature variables, and as ratios capped at 5 for precipitation and vapor pressure).
- The deltas for each variable were interpolated to a 100 km^2 resolution data grid using a bilinear interpolation procedure.

- The interpolated deltas were applied back to a 100 km² resolution grid of climate means observed from 1961 to 1990 to create a high-resolution, gridded time series of possible future weather based on the coarse-grid GCM output.

3.0 Results

3.1. The Response of Vegetation Distribution to the Future Climate Scenarios

The response of vegetation class distribution under the three future climate scenarios was determined by comparing the distribution of the most frequent vegetation type simulated for the 30-year historical period (1961–1990) against the same for the last 30 years (2071–2100) of the future scenarios (Figures 1–3). The overall distribution of the vegetation classes simulated for the historical period is very similar to the observed distribution of natural vegetation types in California (Lenihan et al. 2003). The simulated response of the vegetation classes in terms of changes in percentage coverage (Figure 4) was surprisingly similar under the three future climates. There was agreement on the direction of change (i.e., decrease or increase in coverage) for all but the Desert class, and the amounts of change were comparable for several of the vegetation classes. However, these similarities in the response of class coverage were often the net result of very different responses to each scenario in terms of the spatial distribution of vegetation classes, as discussed below.

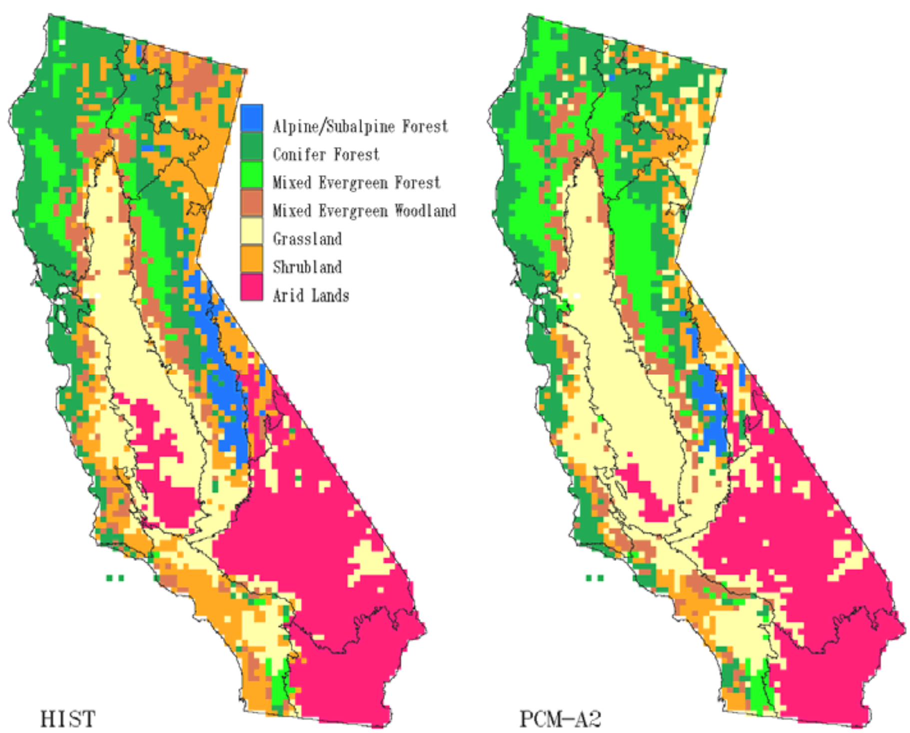

Figure 1. Distribution of the vegetation classes simulated for the historical (1961–1990) and PCM-A2 future period (2070–2099). The vegetation class mapped at each grid cell is the most frequent class simulated during the time period.

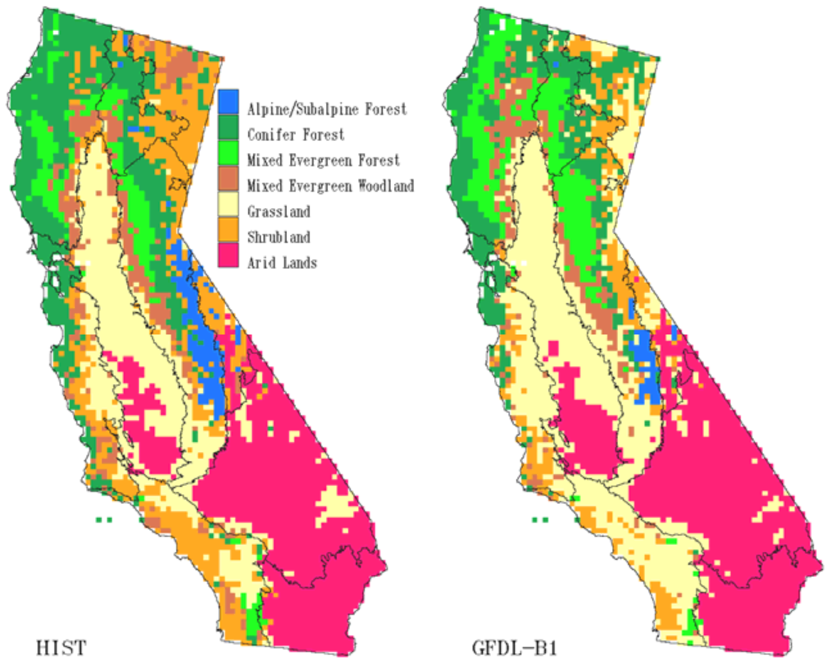

Figure 2. Distribution of the vegetation classes simulated for the historical (1961–1990) and GFDL-B1 future period (2070–2099). The vegetation class mapped at each grid cell is the most frequent class simulated during the time period.

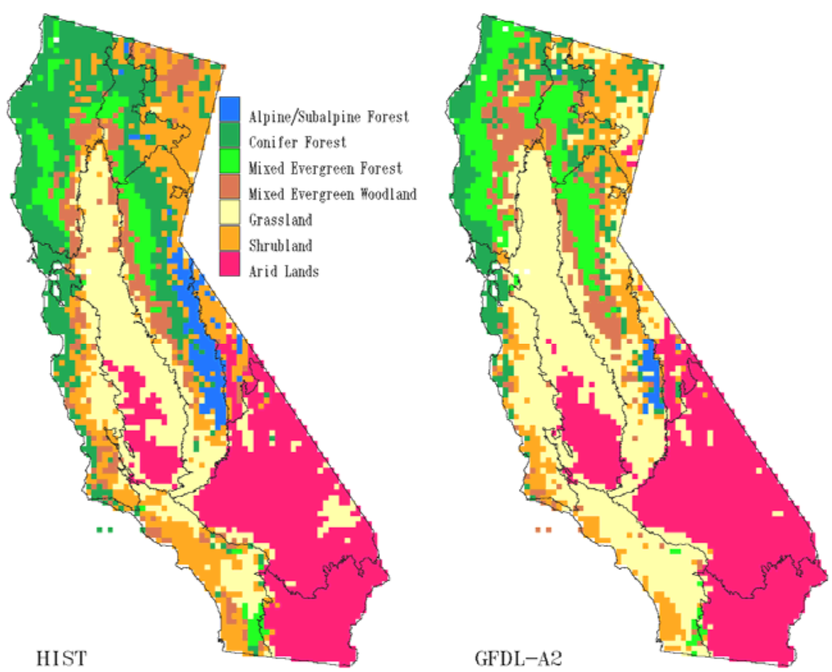

Figure 3. Distribution of the vegetation classes simulated for the historical (1961–1990) and GFDL-A2 future period (2070–2099). The vegetation class mapped at each grid cell is the most frequent class simulated during the time period.

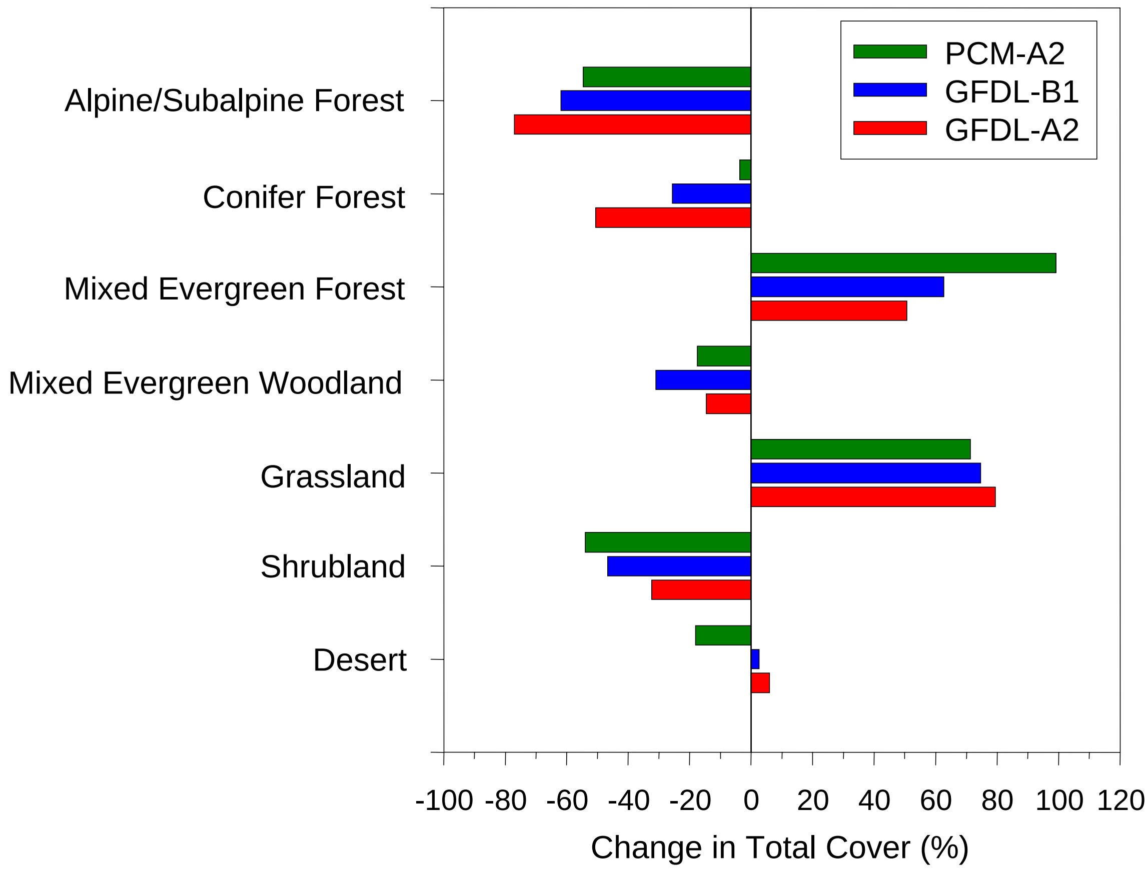

Figure 4. Percentage change in the total cover of the vegetation classes

Significant declines in the extent of Alpine/Subalpine Forest were simulated under all three scenarios, especially under the warmest GFDL-A2 scenario. At high elevation sites the model responded to longer and warmer growing seasons, which favored the replacement of Alpine/Subalpine Forest by other vegetation types.

The simulated extent of forest land in the state (i.e., the combined extent of Evergreen Conifer Forest and Mixed Evergreen Forest) increased relative to the historical extent by 5.5% under the PCM-A2 scenario. Forest cover declined by 0.6% and 5.9% under the GFDL-B1 and GFDL-A2 scenarios, respectively.

Evergreen Conifer Forest declined under all scenarios, but the largest declines were simulated under the warmer and drier GFDL scenarios. Much of the simulated loss of this type was due to replacement by Mixed Evergreen Forest with increases in temperature, but reductions in effective moisture and increases in fire also resulted in losses of Evergreen Conifer Forest to Woodland, Shrubland, and Grassland. The decline in this type to Mixed Evergreen Forest under the cooler and wetter PCM-A2 scenario was largely offset by gains in the semi-arid regions of the Modoc Plateau and Central Coast where Conifer Forest advanced primarily into Shrubland.

Mixed Evergreen Forest increased in extent under all three scenarios. Increases in temperature enhanced the productivity of the mixed evergreen lifeform over the evergreen conifer lifeform, converting Evergreen Conifer Forest to Mixed Evergreen Forest. The expansion of this type was particularly significant under the PCM-A2 scenario, in which higher levels of effective moisture generally promoted the expansion of forest.

Mixed Evergreen Woodland and Shrubland declined under all three scenarios. Under the warmer and drier GFDL scenarios, replacement of these two types, primarily by Grassland, was due to reductions in effective moisture and increased fire. Under the cooler and wetter PCM-A2 scenario, the decline in Woodland and Shrubland was due not only to encroachment by the forest types, but also by Grassland.

Expansion of Grassland under the warmer and drier GFDL scenarios was largely due to reductions in effective moisture. But Grassland gained in extent even under the cooler and wetter PCM-A2 scenario, especially in the semi-arid regions of the state. Here higher levels of effective moisture favored increased productivity of both woody lifeforms and grass. However, increases in grass biomass translated to more fine flammable fuels, promoting more fire that in turn reduced the cover of the woody lifeforms, resulting in the expansion of grasslands.

The Desert type was reduced in extent by the encroachment of Grassland under the wetter PCM-A2 scenario, but increased at the expense of Grassland under the drier GFDL scenarios.

3.2. The Response of Ecosystem Productivity to the Future Climate Scenarios

Simulated ecosystem net primary productivity (NPP) showed considerable interannual and interdecadal variability, especially over the first half of the 21st century when NPP was frequently greater than normal (i.e., greater than the simulated mean annual NPP of 201 teragrams (Tg)—or 221.6 million tons—for the 1895–2003 historical period), even under the drier GFDL scenarios. From about mid-century on, there was a general increasing trend in NPP under the relatively cool and wet PCM-A2 scenario, and a general decreasing trend under the warmest and driest GFDL-A2 scenario (Figure 5a).

A model sensitivity analysis was conducted to assess the contribution of the direct effects of CO_2 (i.e., enhanced plant production and water use efficiency) on the simulated NPP trends. Results indicated that direct CO_2 effects enhanced NPP by about 6% at 500 ppm (concentration at the end of century under the B1 emission scenario) and by about 18% at 800 ppm (concentration at end of century under the A2 emission scenario). The results point to the importance of modeling assumptions regarding the direct effects of rising atmospheric concentrations of CO_2.

Laboratory experiments have shown the beneficial influence of an increase in atmospheric CO_2 for enhancing plant growth and increasing water use efficiency, thereby rendering plants more drought resistant. Results from field experiments are more varied but generally agree on the mitigating effects of CO_2 in the face of global warming (Nowak et al. 2004). Studies from fast-growing early successional stands (free air CO_2 enrichment, or FACE, experiments) have showed a 23% increase in forest NPP for a CO_2 concentration of 550 ppm (Norby et al. 2005), about four times what MC1 simulates at the same concentration. However, Caspersen et al. (2000) showed no evidence of any growth enhancement from CO_2 fertilization in various forests of the eastern United States from 1930 to 1980. Moreover, the latest results from a European study (Körner et al. 2005) on a mature western European deciduous forest showed no growth enhancement of

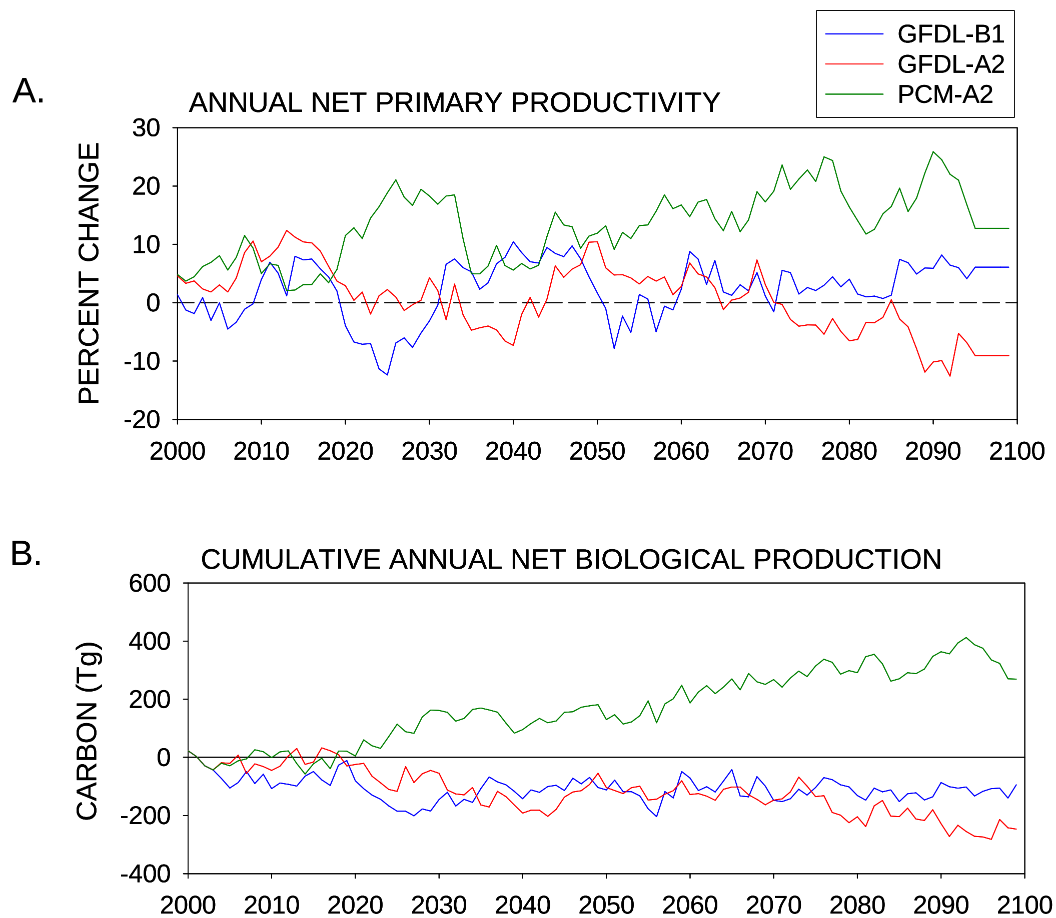

Figure 5. (A) percent change in annual net primary production (NPP) relative to simulated mean annual NPP for the 1895–2003 historical period, and (B) cumulative net biological production over the future period. NPP trends have been smoothed using a 10-year running average.

leaf area or biomass. The CO_2 fertilization effect has also been shown to be constrained by limiting factors such as soil water and nutrient availability, even in young stands (Oren et al. 2001; Norby et al. 2005). These limiting factors in essence control the "carrying capacity" of the ecosystem, whereas the CO_2-enhanced increase in NPP would likely increase the rate of growth toward the environmentally constrained carrying capacity.

MC1 appears to have a CO_2 effect that is slightly low compared to the results of FACE studies, thus possibly producing a more sensitive response to temperature-induced drought (Nowak et al. 2004). However, since MC1 simulates the growth of both mature and early successional stands which may be constrained by water availability, CO_2 enhancement may not be greatly underestimated in the model. Data from mature forests subject to natural climatic stress that could invalidate model assumptions are currently lacking.

Net biological production (NBP) is the balance between carbon gained by the ecosystem via net primary productivity, and carbon lost from the ecosystem via decomposition and consumption by fire. The simulated trend in cumulative NBP under the cooler and wetter PCM-A2 scenario (Figure 5b) showed a steady increase over the course of the future period, resulting in the accumulation of 321 Tg of new ecosystem carbon in California by the end of the century, a 5.5% increase over total carbon stocks simulated for the historical period (Table 2). New soil/litter carbon accounted for over 80% of the new carbon sink under the PCM-A2 scenario (Figure 6a). The remaining 20% accumulated as live vegetation carbon, 80% of which was new grass carbon (Figure 6c).

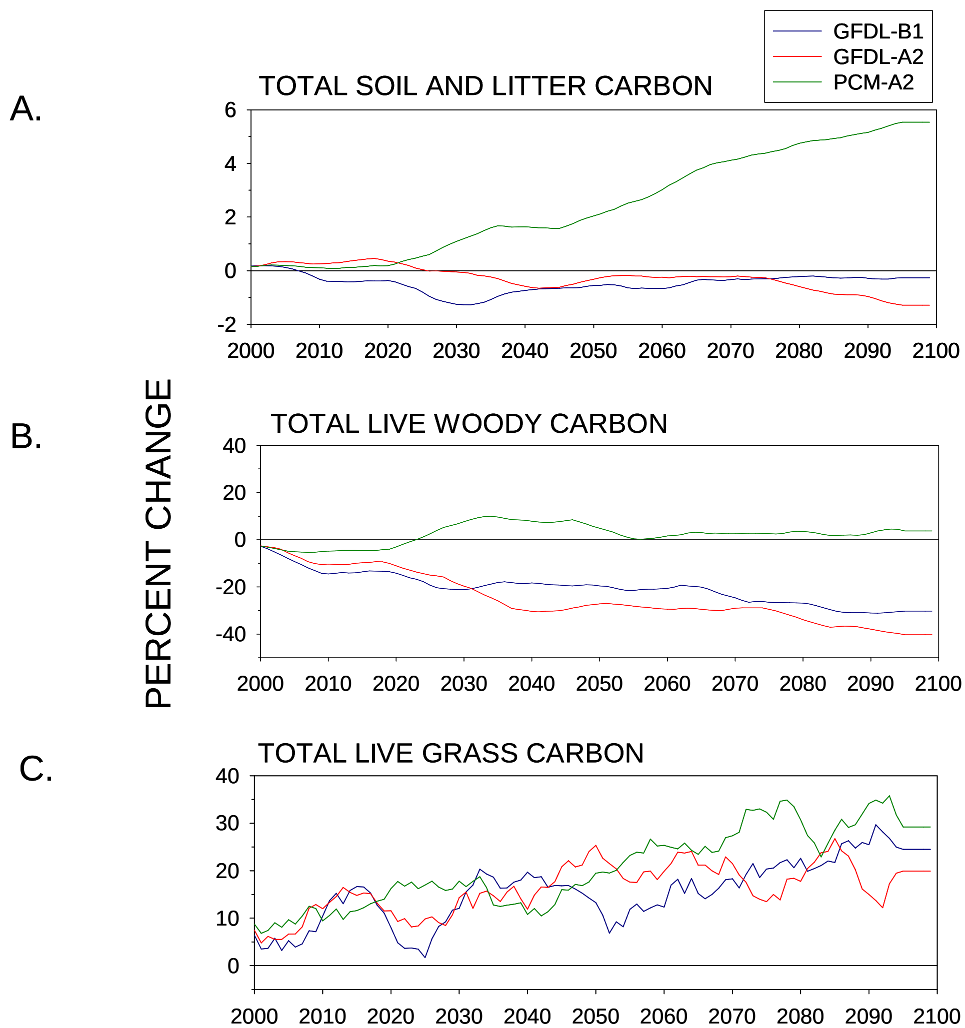

Figure 6. Percent change in (A) total soil and litter carbon, (B) total live woody carbon, and (C) total live grass carbon relative to simulated mean annual values for the 1895–2003 historical period. All trend lines have been smoothed using a 10-year running average.

The simulated trends in cumulative NBP under the warmer and drier GFDL scenarios (Figure 5b) showed a steady decrease over the course of the future period, resulting in the loss of 76 and 129 Tg (83.8 million and 142.2 million tons) of total ecosystem carbon by the end of the century under the B1 and A2 emission scenarios, respectively (Table 2). These losses represent a decline in total carbon stocks of 1.3% (B1) and 2.2% (A2) relative to simulated historical levels. Losses of live vegetation carbon accounted for 80% (B1) and 67% (A2) of the declines in total ecosystem carbon. Losses in total vegetation carbon under the GFDL scenarios were a net result of woody carbon losses and grass carbon gains (Figures 6b,c). Relative to simulated historical levels, total woody carbon declined by 29% while total grass carbon increased by 22% by the end of the century under the B1 emission scenario. Under the A2 scenario, woody carbon declined by 36% while grass carbon increased by 20%.

Table 2. Size of the historical and future carbon pools simulated for the state of California, USA. All values are in teragrams of carbon. Historical values are the mean masses simulated for the 1895–2003 period. Values for the future climate scenarios are mean masses simulated for the 2070–2099 period.

Carbon Pool	Historical	GFDL-B1	GFDL-A2	PCM-A2
Total Ecosystem	5841	5765	5712	6162
Soil and Litter	5359	5344	5316	5624
Total Live Vegetation	482	421	396	538
Live Wood	330	235	213	340
Live Grass	152	186	183	198

3.3. The Response of Fire to the Future Climate Scenarios

The future trends in simulated total area burned in California were characterized by considerable interannual variability (Figure 7a), but for nearly every year during the future period, total area burned was greater than the simulated mean total annual area burned over the 1895–2003 historical period. By the end of the century, predicted total annual area burned ranged from 9% to 15% greater than normal. The greater extent of grasslands (Figures 1–3) and increasing trends in total grass carbon (Figure 6c) promoted greater rates of simulated fire spread and thus more area burned under all three scenarios.

Predicted future trends in annual total biomass burned (Figure 7b) were linked to the simulated trends in NPP (Figure 5a). Under the relatively cool and wet PCM-A2 scenario, higher than normal NPP throughout much of the scenario period produced more fuel biomass for consumption. Biomass consumption was about 18% greater than the historical norm by the end of the century under this scenario. Under the warmer and drier GFDL scenarios, simulated biomass consumption was also greater than normal for the first few decades of the century as drought-stressed woodlands and shrublands burned and were converted to grassland. After this transitional period, lower than normal NPP produced less fuel, and biomass consumed was at, or below, the historical norm by the end of the century under the GFDL scenarios.

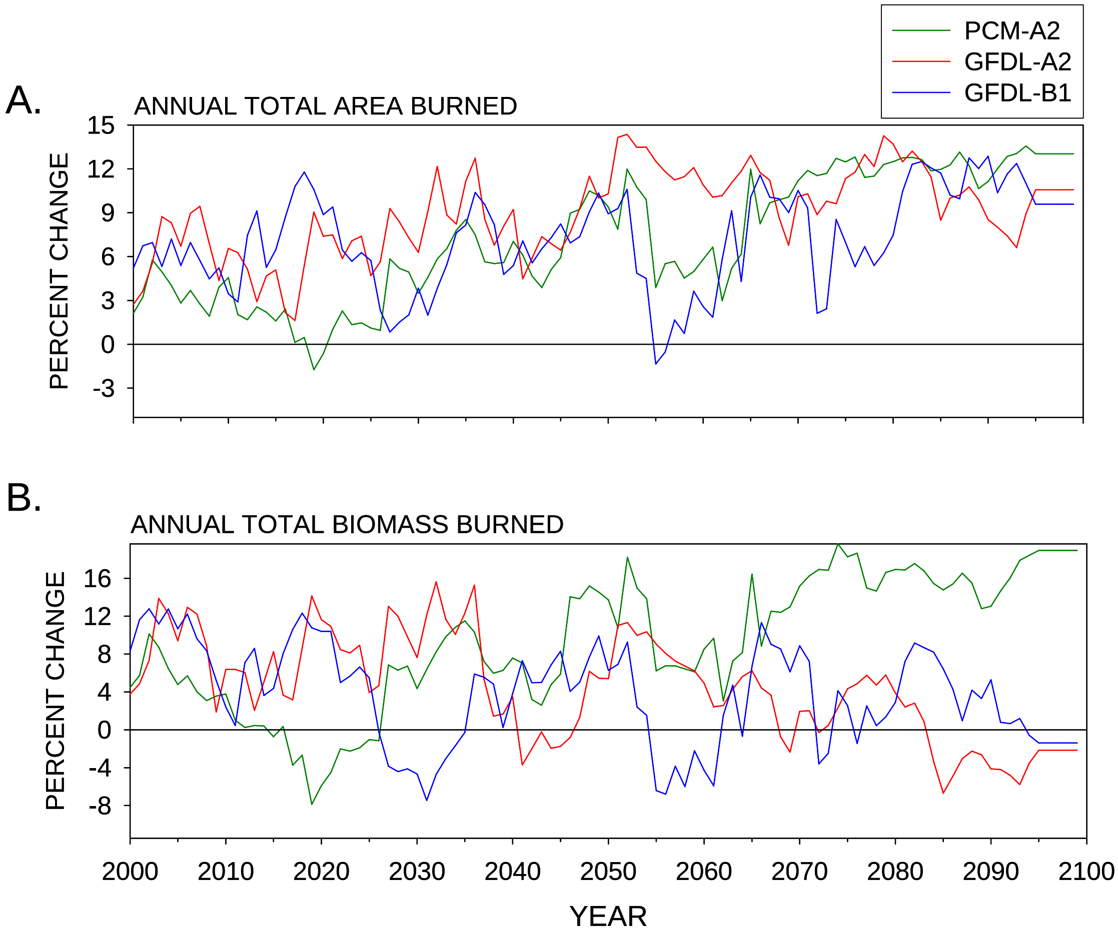

Figure 7. (A) Percent change in annual total area burned relative to the simulated mean annual total area burned for the 1895–2003 historical period, and (B) Percent change in annual total biomass consumed relative to the simulated mean annual biomass consumed for the historical period. All trend lines have been smoothed using a 10-year running average.

Summer months were warmer and persistently dry across California under all three scenarios, so drier than normal fuels were also a pervasive factor in the higher than normal annual total area burned simulated by the model. However, spatial variation in the simulated changes in area burned under each scenario (Figure 8) was largely a product of changes in vegetation productivity and in the competitive balance between woody plants and grasses. Under all three scenarios, the greatest increases in annual area burned were simulated along the central and south coasts, in the northern Great Valley, on the Modoc Plateau, and along the eastern edge of the Sierra Nevada. Here the response of the model to decreased effective moisture under the GFDL scenarios was an increase in the dominance of the more drought-tolerant grasses. And although the response to moderate increases in effective moisture under the PCM-A2 scenario was increased productivity of both lifeforms, increases in grass biomass translated to more fine flammable fuels in the model, promoting more fire that in turn reduced the density of the woody lifeforms. So under all three scenarios, the response of the model in these semi-arid regions was characterized by a shift towards more grass-dominated vegetation (Figures 1–3) which in turn promoted higher rates of fire spread, and thus more annual area burned.

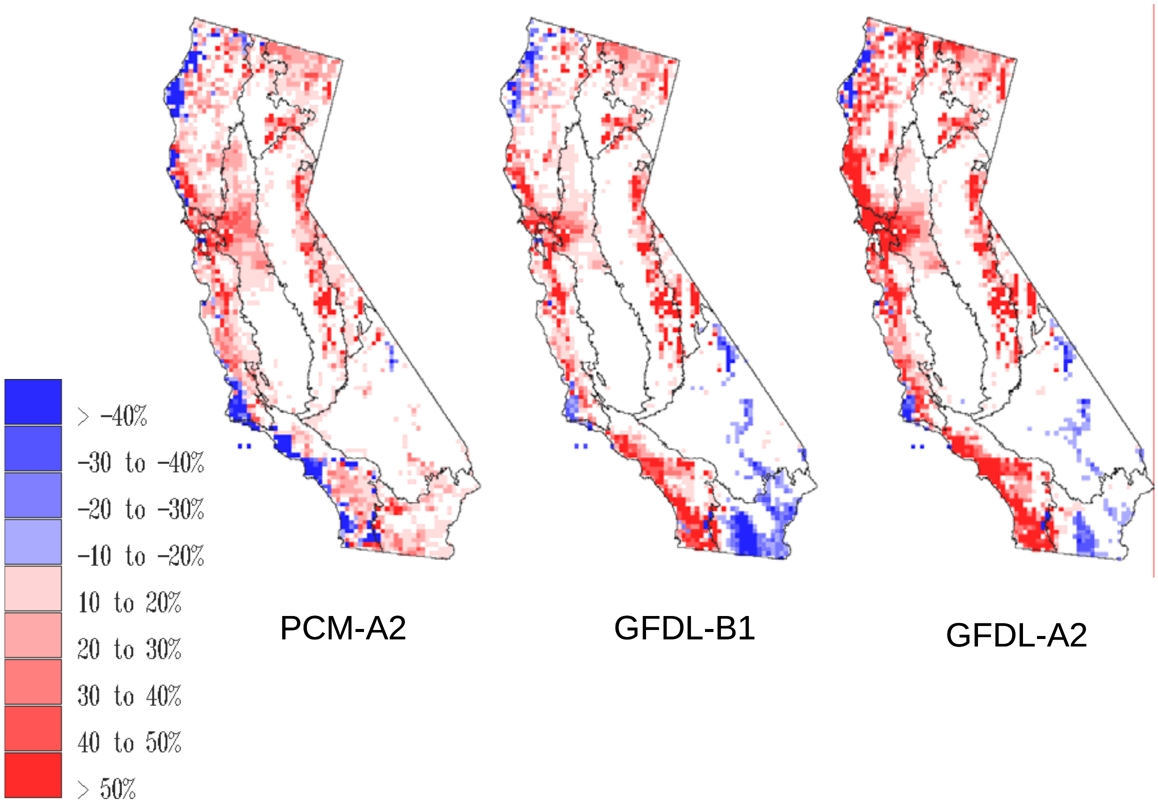

Figure 8. Percent change in mean annual area burned for the 2050–2099 future period relative to the mean annual area burned for the historical period (1895–2003)

4.0 Discussion

The results of the three new MC1 simulations for California, like those generated under other future climate scenarios (Lenihan et al. 2003; Hayhoe et al. 2005), demonstrate certain ecosystem sensitivities and interactions that are likely to be features of the response of both natural and semi-natural (e.g., managed forests and rangelands) systems to a relatively certain rise in temperature and less-certain changes in precipitation. An increase in temperature could increase vegetation productivity given adequate moisture availability, especially in cooler regions of the state. An increase in temperature could also alter forest composition by increasing the competitiveness of evergreen broadleaf hardwood species, which are less tolerant of low winter temperatures than are conifers (Woodward 1987).

The model results indicate fire will play a critical role in the adjustment of semi-arid vegetation to altered precipitation regimes, be it slowing or limiting the encroachment of woody vegetation into grasslands under wetter conditions, or hastening the transition from woody communities to grassland under drier conditions. Field observations from coastal central California show that these woody communities have weak resilience to high fire frequency and are readily replaced by grassland under high fire frequency (Keeley 2002; Callaway and Davis 1993). The net loss and redistribution of woodland in California simulated by MC1 under the three future climate scenarios in this study and under four others (Lenihan et al. 2003; Hayhoe et al. 2005) are also consistent with results from a study using a statistical climate envelope model developed for California oak woodlands and a higher-resolution climate scenario generated by a regional-scale climate model (Kueppers et al. 2005).

The model results from this study and other MC1 simulations for California also suggest that changes in fire and shifts in the relative dominance of woody and grass lifeforms could buffer the effect of different climatic perturbations on total ecosystem carbon storage. Under a wetter climate, increased carbon storage with increased vegetation productivity could be limited by greater losses to wildfire. Under a drier climate, decreased carbon storage with the decreased vegetation productivity could be limited by decreased rates of decomposition and a shift towards greater dominance of grass lifeforms which are better adapted to more frequent fire and are more effective contributors to soil carbon stocks.

While none of the MC1 simulations for California should be taken as predictions of the future, it is evident from the results that all the natural ecosystems of California, whether managed or unmanaged, are likely to be affected by changes in climate. Changes in temperature and precipitation will alter the structure, composition, and productivity of vegetation communities, and wildfire may become more frequent and intense. In the near term, wildfire increased under all scenarios, whether they were wetter or drier. The incidence of pest outbreaks in forests stressed by a changing climate could act as a positive feedback on the frequency and intensity of fire. Drought can act synergistically with both pests and fire, in some cases producing an overshoot in the reduction of ecosystem biomass and integrity, that is, driving the ecosystem well below its drought-reduced carrying capacity. Nonnative species preadapted to disturbance could colonize altered sites in advance of native species, preventing the already problematical redistribution of natives across a landscape highly fragmented by land-use practices.

Considerable uncertainty exists with respect to the regional-scale impacts of global warming. Much of this uncertainty resides in the differences among different GCM climate scenarios and assumed trajectories of future greenhouse gas emissions, as illustrated in this study. Furthermore, California is in a transitional location between the very wet Northwest and the very dry Southwest. Although global precipitation is expected to increase under global warming, minor uncertainties in shifts in the stormtracks that separate these wet and dry regions could result in either wetter or drier conditions, rendering regional precipitation patterns especially difficult to forecast for California.

In addition, ecosystem models and their response to projected climate change can always be improved through careful testing and enhancement of model processes. Dynamic vegetation models are an especially new technology and are still undergoing rapid development to improve existing algorithms and to introduce new ones. For example, this study's MC1 simulations of future changes in fire area and biomass burned were generated under the assumptions of constantly available ignition sources (e.g., lightning or human-caused ignitions) and no fire suppression. Fire simulations generated under more realistic assumptions await the addition of new, and likely complex, functions to the fire model. But these functions may require new sets of assumptions with high levels of uncertainty (e.g., the future rates of population growth or resources available for fire suppression). Furthermore, wind-related weather conditions (e.g., Santa Ana and Diablo winds) strongly associated with wildfire spread in California are poorly represented by GCM-scale wind fields, and more research is required to establish the sensitivity of these events under greenhouse gas forcing (Miller and Schlegel 2006; this study).

Nevertheless, the results of this and previous studies underscore the potentially large impacts of climate change on California ecosystems, and the need for further analyses of both future climate change and terrestrial ecosystem responses. It must be stressed that natural resource management historically has been based on a view that the future will echo the past. Under rapid climate change, that premise is no longer tenable. Although we must continue to strive for improved resource forecasting technology, especially coupling the forecasts across different disciplines, such as atmospheric dynamics, ecosystems, water resources, and social systems, we will never have the degree of certainty of the future that we previously presumed. Our management philosophy must adjust to one of husbanding complex systems through rapid change, while minimizing catastrophic disturbance and preserving the sustainable functioning of ecosystems and their services.

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6.0 Glossary

A2 A "high emissions" scenario corresponding to a CO_2 concentration by the end of the 21st century more than three times the pre-industrial level.

B1 A "low emissions" scenario with a doubling of pre-industrial CO_2 by the end of the 21st century.

CO_2	Carbon dioxide, the principal greenhouse gas
DGVM	Dynamic general vegetation model
FACE	Free air CO_2 enrichment
GCM	General circulation model
GFDL model	Geophysical Fluid Dynamics Laboratory model, a GCM
MC1	MAPSS-CENTURY model, version 1, a DGVM
NBP	Net biological production
NCAR	National Center for Atmospheric Research
NPP	Net primary productivity
PCM	Parallel climate model, a GCM
PRISM	Parameter-Elevation Regression on Independent Slopes Model
VEMAP	Model developed by the Vegetation-Ecosystem Modeling and Analysis Project