Arnold Schwarzenegger
Governor

ECOSYSTEM FEEDBACKS TO CLIMATE CHANGE IN CALIFORNIA: INTEGRATED CLIMATE FORCING FROM VEGETATION REDISTRIBUTION

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
Lara Kueppers, University of California, Merced
William Riley, Lawrence Berkeley National Laboratory
Jiming Jin, Utah State University
Zack Subin and Danielle Christianson, University of California, Berkeley
Margaret Torn, University of California, Berkeley and Lawrence Berkeley National Laboratory

December 2008
CEC-500-XXXX-XXX

Prepared By:
University of California, Merced

Lara M. Kueppers
Merced, CA 95344
Commission Contract No. **500-02-004**
Commission Work Authorization No: **MR-069**

Prepared For:
Public Interest Energy Research (PIER)
California Energy Commission

Gina Barkalow
Contract Manager

Linda Speigel
Program Area Lead
Energy-Related Environmental Research

Mike Gravely
Office Manager
Energy Systems Research

Martha Krebs, Ph.D.
PIER Director

Thom Kelly, Ph.D.
Deputy Director
ENERGY RESEARCH & DEVELOPMENT DIVISION

Melissa Jones
Executive Director

Acknowledgments

The authors thank Ron Neilson, Jim Lenihan, and Sandra Brown for providing scenarios of vegetation change in California, and Sebastien Biraud and Ramona Butz for helping convert various files to common resolutions and projections.

Please cite this report as follows:

Kueppers, L. M., W. J. Riley, J. Jin, Z. M. Subin, D. S. Christianson, and M. S. Torn. 2008. *Ecosystem Feedbacks to Climate Change in California: Integrated Climate Forcing from Vegetation Redistribution.* California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-xxx-xxx-xxx.

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), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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 are focused on the following RD&D program areas:

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

Ecosystem Feedbacks to Climate Change in California: Integrated Climate Forcing from Vegetation Redistribution is the final report for the Ecosystem Feedbacks to Climate Change in California: Integrated Climate Forcing from Vegetation Redistribution project (contract number UC 500-02-004, work authorization MR-069) conducted by University of California, Merced, Lawrence Berkeley National Laboratory, Utah State University and the University of California, Berkeley. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

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

Table of Contents

List of Figures

List of Tables

Abstract

Changes in ecosystems due to climate change or from climate mitigation measures may trigger follow-on changes in regional climate. These climate-ecosystem feedbacks are important because they may cause future climate change to be larger or smaller than predicted without considering these feedbacks. They also mean that climate mitigation involving land cover change, such as C sequestration by afforestation, may have local climate effects as well as global ones. This study uses a set of regional climate model (WRF-CLM3) simulations to quantify the climate effects of changes in ecosystem distribution under historical and future climate. The sensitivity of regional climate projections to vegetation change was investigated using three different vegetation distributions (Historic Native, Future Native, and Future Native + Afforestation) and two different global climate scenarios (GFDL 20th century and GFDL A2 Future). Results from 10-year model simulations suggest that vegetation change alone can lead to both increases and decreases in July midday temperatures of -1.5 to +5 °C, depending on subregion and vegetation-type change. Vegetation change accounts for up to 60% of statewide temperature change in snow-free regions due to the combination of large-scale (global) climate forcing and regional vegetation change. Afforestation may have effects on climate as well; the simulations indicate that a shift from shrubland to forest results in local temperature decreases of ~0.5-2 °C in snow-free regions. These temperature effects are the consequence of a complex set of changes to the surface energy budget and lower atmosphere.

Keywords: climate-ecosystem feedbacks, regional climate model, afforestation, climate change, WRF-CLM

Executive Summary

Introduction

California is vulnerable to climate change, with changes in temperature and precipitation likely to affect water resources, the health of citizens, and the diverse natural ecosystems that Californians prize. In addition to feeling the effects of climate change, ecosystems affect climate, so that ecosystem responses to climate change may trigger follow-on changes in regional climate. This set of two-way interactions is known as climate-ecosystem feedbacks, and has not been well studied either globally or in California. Specifically, changing vegetation distribution will result in changes in energy, water, and/or CO_2 fluxes, and these changes will depend on the location and types of vegetation shifts. In this study, the relative importance of climate-ecosystem feedbacks to future predictions of climate change in California was estimated, with a particular emphasis on shifts in the geographic distribution of native ecosystems and of increasing forest area through afforestation. Ecosystem types and subregions of California that experienced the largest climate-ecosystem interactions were identified.

Purpose

To improve understanding of the climate-ecosystem feedbacks that will influence California's climate over the next 80 years.

Project Objectives

- To obtain preliminary information on the effects of afforestation and shifts in natural vegetation on surface energy budgets (radiation, sensible heat, latent heat) and near-surface temperatures and snow.

- To define future, related research needs

Project Outcomes

The growing literature on ecosystem and climate feedbacks was reviewed.

A state-of-the-art modeling framework, using coupled land-surface (CLM) and atmosphere (WRF) models, was applied in historic and end-of-century scenarios with historic vegetation, an estimate of future natural vegetation, and future natural vegetation with afforestation.

Analyses were conducted to isolate the effects of changes in climate alone, vegetation changes alone, and combinations of climate and vegetation changes on surface air temperature. The results of this study indicated that up to 60% of expected changes in near-surface air temperature could result from changes in vegetation, with large differences across the state and between seasons. Afforestation substantially altered snow cover in some regions and near-surface air temperatures in many parts of the state.

Conclusions

The key findings from this study were the following:

- In the absence of vegetation change, California regional climate warms substantially between historical and future climate scenarios.
- Independent of large-scale climate change, the effect of vegetation changes on near surface air temperatures varied from positive to negative across the state, with the most pronounced effect during summer.
- The overall projected change in regional temperatures as a consequence of both large-scale (global) climate change and regional vegetation change was large.
- Across California, the model simulations suggest that up to 60% of total projected near surface air temperature change in snow-free regions comes from vegetation changes, with large variations depending on the region and time of year.
- A complex set of changes in radiation, mass, and energy budgets associated with vegetation changes led to very different changes in near-surface air temperatures in subregions of California. Further work is required to explain these different climate responses.
- Average midday air temperature decreased in July with afforestation in regions of non-marginal snow cover, except one area in the Sierra foothills where decreased snow cover caused a temperature increase. Further work is required to explain these varied responses.

Recommendations

This exploratory study points to several areas of fruitful future research. The estimates from this sensitivity study would benefit from further improvements to the regional climate model system, including development of the dynamic vegetation module for use with California specific plant functional types as defined in this study. Additional model experiments of longer duration would also enable characterization of the role of vegetation change in extreme climate events (e.g., heat waves) and how various afforestation scenarios affect local climate. Finally, field measurements to verify both the magnitude of vegetation effects and the mechanisms by which they influence local and regional climate would increase confidence in these and other model results.

If the effects of afforestation seen in this exploratory study prove robust after further analysis, then it would be important for California policy makers to note that afforestation has a regional cooling effect in California, in addition to the intended global cooling effect of reducing atmospheric CO_2 concentrations. However, caution is required in that the afforestation regions used in the study may not naturally support forest under future warmer climate.

Benefits to California

Understanding the effects of vegetation changes, including intentional afforestation, on climate change over the next 80 years is important for California policies on adaptation, mitigation, and prediction. This study indicates that these effects can be large as well as spatially and temporally heterogeneous.

1.0 Introduction

Because California's economy and the global economy currently rely on fossil fuels for electricity generation, greenhouse gases released when the fossil fuels are burned have accumulated in the atmosphere and are altering global climate. California is vulnerable to climate change, with changes in temperature and precipitation likely to affect water resources, the health of citizens, and the diverse natural ecosystems that Californians prize (Luers et al. 2006).

In addition to feeling the effects of climate change, ecosystems affect climate, so that ecosystem responses to climate change may trigger follow-on changes in regional climate. This set of two-way interactions is known as climate-ecosystem feedbacks (Foley et al. 2003), and has not been well studied either globally or in California. Climate-ecosystem feedbacks are important because they may cause future climate change to be larger or smaller than predicted without considering these feedbacks. Because the response of ecosystems to climate change is largely region-specific, and because some ecosystem changes (particularly shifts in the geographic distribution of vegetation types) have their largest climatic effects regionally, an understanding of these feedbacks at the regional scale is critical. Specifically, changing vegetation distribution will result in changes in energy, water, and/or CO_2 fluxes, and these changes will depend on the location and types of vegetation shifts.

There are numerous gaps in the understanding of climate-ecosystem feedbacks, including the rate at which ecosystems respond to climate change, the magnitude of ecosystem responses to climate, the accuracy of estimates of ecosystem influence on climate, and the way in which these elements are represented in dynamic models of the climate system. A better understanding of climate-ecosystem feedbacks, including the time period and area over which they operate, will contribute to better predictions of regional climate change. It will also help inform policy options for mitigating greenhouse gas emissions, particularly whether afforestation (whereby trees are planted to remove carbon dioxide from the atmosphere and store it in living biomass) will yield climatic benefits for California.

In this study, the relative importance of climate-ecosystem feedbacks to future predictions of climate change in California was estimated, with a particular emphasis on shifts in the geographic distribution of native ecosystems and of increasing forest area through afforestation. Ecosystem types and subregions of California that experienced the largest climate-ecosystem interactions were identified.

1.1. State of the Science

Currently, the most sophisticated global climate models (GCMs) have a very limited representation of ecosystem feedbacks (Torn and Harte 2006). One inherent challenge to the accurate representation of ecosystem feedbacks in GCMs is that dramatic variation in ecosystem properties and behavior exists at very small spatial scales relative to the horizontal resolution of the typical GCM. Regional climate models (RCMs) are better able to capture this fine scale variation, but have been a step behind global models in terms of incorporating ecosystem processes and their effects on climate.

State-of-the-art regional climate-model studies have predicted future anthropogenic climate change in California, including predictions for above-average temperature increases at higher elevations, a shift in the proportions of winter rain and snow, earlier spring snowmelt, more severe heat waves, and increases in winds that drive coastal water upwelling (Snyder et al. 2002, Snyder et al. 2003, Leung et al. 2004, Snyder and Sloan 2005, Bell and Sloan 2006). These studies have revealed how and where California is most vulnerable to global climate change, but cannot make predictions of changes in ecosystem distribution or behavior. As a result, any ecosystem responses to climate change are not represented, nor are the climate feedbacks that may result from shifts in vegetation distribution.

Another kind of model, called a dynamic vegetation model (DVM), has been used to predict potential shifts in vegetation distribution, ecosystem productivity, and fire frequency. Simulations have been performed with a combined biogeographical-biogoechemical model called MC1 for California, based on scenarios of climate change from GCMs (Lenihan et al. 2003, Lenihan et al. 2006). Grouping California's vegetation into seven categories. MC1 found net increases in the area covered by desert, grassland, and mixed evergreen forest at the expense of conifer forest and alpine/subalpine forest under business-as-usual climate change scenarios. So far, these studies have not customized vegetation properties to match specific California vegetation types, although they do capture some important ecosystem processes such as fire and carbon cycling. These studies do not quantify the effects of ecosystem change on climate forcing, only the effects of climate change on ecosystems. And in most cases, the ecosystem model has been driven by output from coarse-resolution GCMs, which can yield qualitatively different predictions for vegetation shifts than using output from RCMs (Kueppers et al. 2005).

One published study has sought to quantify this two-way climate-ecosystem feedback in the western United States by using an equilibrium vegetation model to estimate ecosystem responses, and then using the new land surface within an RCM to further modify climate (Diffenbaugh 2005). This study found that, in some subregions, up to 60% of the seasonally averaged temperature change resulting from CO_2 driven climate change was due to feedbacks from the land surface. This study suggests that feedback strength could be important in California via both albedo changes and changes in soil moisture. A critical limit of this study is that it used a fairly simple land surface model to translate the changes in ecosystem distribution into changes in climate forcing by the land surface. The land surface model had a very general treatment of ecosystem (biome) types, and did not represent the unique character of California's vegetation very well. For example, the phenology of vegetation assumes a summer growing season for grasslands, while California's grassland growing season is during the winter and spring. This difference significantly affects seasonal variation in albedo and evapotranspiration. In addition, Diffenbaugh (2005) did not address how promotion of afforestation could also alter climate.

Large-scale changes in land use for mitigating greenhouse gas emissions via carbon sequestration in trees could have local and regional climate effects. In the Eastern U.S., one study found that with economically feasible afforestation ($100 Mg/C) on current crop and pasture land, July evapotranspiration increased and temperature decreased by up to 0.3°C in the modified regions (Jackson et al. 2005). In California, another study that looked at the potential for planting forests on rangeland deemed environmentally and economically suitable for carbon

sequestration indicated that up to 21 million acres could be considered for carbon offsets via afforestation, depending on cost and the timeframe of interest (Brown et al. 2004). Approximately 79% of CO_2 emissions from electricity generation could be offset via afforestation at a cost of $13.6 per metric ton of CO_2 or less. The relevant areas are distributed throughout the state, but a few counties have considerable potential for afforestation.
The potential strength of these interactions is investigated in this report, using scenarios of vegetation change and an RCM customized for California ecosystems.

2.0 Methods

2.1. Experimental Design

This study uses a set of RCM simulations to quantify the climate effects of changes in ecosystem distribution under historical and future climate. The model sensitivity experiments investigated combinations of three different vegetation distributions (Historic Native, Future Native, and Future Native + Afforestation) and boundary conditions from two different GCM scenarios (GFDL 20^{th} century and GFDL A2 Future) (Table 1). None of the experiments represented urban or agricultural land cover or changes in these cover types. Other factors that influence regional climate including aerosols and agricultural irrigation also were not included in the present study. Atmospheric CO_2 concentrations were held constant at 380 ppm in the RCM for all cases.

Table 1. Climate and cover type for the four simulations performed.

	Vegetation cases		
Climate cases	*Historic Native*	*Future Native*	*Future Native + Afforestation*
GFDL 20^{th} c.	HCHV		
GFDL A2 future	FCHV	FCFV	FCAV

2.2. Model Descriptions

Over the last ~15 years, RCMs have become increasingly important for predicting the regionally specific impacts of global climate change. RCMs are similar to GCMs in that they represent atmospheric dynamics and interactions between the land surface and atmosphere, and can simulate the climate system over long time-scales (years to centuries). Unlike GCMs which are typically run at ~100+km resolution, RCMs can be run at higher resolution, on the order of 10-50km, and are only run in a limited geographic domain. As a result, RCMs better capture climate processes influenced by topographic heterogeneity, coastal dynamics, and heterogeneous land cover and land use. In addition, most global studies have demonstrated that the largest climate impacts of land-cover/use change occur within the modified region (Bounoua et al. 2002, DeFries et al. 2002). Because RCMs can capture vegetation change at relatively small spatial scales where topography may also be varying strongly, an RCM approach is well suited to understanding climate-ecosystem interactions in California.

2.2.1. WRF-CLM3

The RCM that was used for this study is the Weather Research and Forecasting (WRF) model developed by the National Center for Atmospheric Research (NCAR). This model is a state-of-the-art non-hydrostatic numerical weather prediction model. First released in 2000, WRF is now the most widely used community weather, climate and water resources forecasting and research model in the world. WRF consists of a computational fluid dynamics core using explicit finite-difference approximation plus different physics modules to represent atmospheric processes. The model uses a terrain-following, hydrostatic-pressure vertical coordinate with the top of the model being a constant pressure surface. The horizontal grid is the Arakawa-C grid. The time integration scheme in the model uses the third-order Runge-Kutta scheme, and the spatial discretization employs second to sixth order schemes. WRF includes an advanced three-dimensional variational data assimilation system, and a software architecture allowing for computational parallelism and system extensibility. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers.

The Community Land Model version 3 (CLM3) was recently coupled with WRF to improve simulations of land surface processes as well as heat and water flux exchanges between the land surface and atmosphere. CLM3 has been shown to be accurate in describing snow, soil, and vegetation processes for global and regional applications (Bonan et al. 2002b; Zeng et al. 2002; Jin and Miller 2008). CLM3 includes a 5-layer snow scheme, a 10-layer soil scheme, and a single layer vegetation scheme. An advanced 10-layer lake model is also coupled with CLM3. Solid ice and liquid water are described in the snowpack as prognostic variables. A sophisticated snow compaction scheme is used to calculate the height and density of snow, where the snow density is a critical variable for describing the water and heat transfer within the snowpack (Jin et al. 1999). The model physically describes frozen soil processes and their impact on soil properties. The soil is divided into 19 categories defined as percentages of sand and clay. The two-stream approximation (Dickinson 1983; Sellers 1985) is applied to vegetation to calculate solar radiation reflected and absorbed by the canopy as well as its transfer within the canopy. A maximum of eight sub-grids per model grid is included in CLM3 to better represent subgrid heterogeneity of the land surface. CLM3 represents vegetation as plant functional types (PFTs), which occur in mixtures within the vegetated fraction of each grid cell. The plant types differ in properties that determine partitioning of solar radiation, root distribution in the soil, aerodynamics at the vegetation-atmosphere interface, and rates of photosynthesis (Oleson et al. 2004). Once calculations are performed at the PFT level, energy, water and momentum fluxes are aggregated to the grid cell level and passed to the atmospheric model. CLM3 has 15 different PFTs currently specified (11 tree types, 3 grass types and 1 crop type). The version of CLM used in global scale simulations has vegetation that is responsive to atmospheric change (dynamic vegetation), but this feature has not yet been tested in WRF, and is not used in the current study. Additional technical details on CLM3 are provided in Oleson et al. (2004).

WRF-CLM3 has been extensively tested with different combinations of 10 km resolution atmospheric physical schemes with a focus on the California area (unpublished data, J. Jin). In previous work, the optimal combination was identified and a ten-year integration was performed for this region. The WRF-CLM3-simulated precipitation and temperature fields were compared with observations and a couple of other RCMs, as part of an RCM intercomparison project managed by California Energy Commission. The results showed that the calibrated WRF-CLM3 produced realistic winter precipitation simulations (Miller et al. 2007). Without calibration, WRF coupled with the Rapid Update Cycle (RUC) land surface model (Smirnova et al. 2000) dramatically overestimated the precipitation especially over the mountainous areas. In addition, both versions of WRF simulated the temperature spatial pattern well. These previous studies indicate that WRF-CLM3 can produce faithful representations of the regional climate system over California.

In the present study, WRF-CLM3 was configured with 20 km horizontal grid spacing and with 30 vertical layers from the surface to 20 km altitude. In order to properly represent planetary boundary layer processes, the vertical layers were more closely spaced near the surface and widely spaced in the upper atmosphere. The domain was centered on 37.0 N 120.0 W and comprised 74 grid cells in the east-west direction and 79 in the north-south direction, with a Lambert Conformal projection. WRF was configured with the RRTM longwave radiation scheme, the Goddard shortwave radiation scheme, the Monin-Obukhov (Janjic) surface atmospheric layer scheme, the Mellor-Yamada-Janjic TKE planetary boundary layer scheme, the Grell-Devenyi ensemble cumulus convection scheme, and WSM 3-class simple ice scheme for microphysics. Outside of California in CLM, 24 United States Geological Survey (USGS) land cover types specified land cover, which were then disaggregated into fractional cover by 3-4 standard CLM3 PFTs (of 16 possible) including bare ground as in Miller et al. (2007). Within California, 16 new PFTs and land cover source data from the MC1 dynamic vegetation model were used (see below). The spatial distribution of land cover and PFTs varied according to the vegetation scenario. As a consequence, 32 different PFTs were used throughout the domain. Thirteen-year simulations were performed for each of the cases (1968-1980 for the 20th c. runs, 2058-2070 for the future climate runs) discarding the first 3 years of output and analyzing the final 10 years.

2.2.2. Geophysical Fluid Dynamics Laboratory Model Lateral Boundary Conditions

Lateral atmospheric boundary conditions and sea surface temperatures were provided to WRF-CLM3 every 6 hours from the GFDL GCM (Delworth et al. 2006). For the historical climate cases, atmospheric and oceanic model output from the GFDL 2.1 20C3M(run2) case (http://nomads.gfdl.noaa.gov/CM2.X/CM2.1/available_data.html) were utilized. This global model produced a realistic seasonal cycle of temperature and precipitation in California, and interannual variability in climate reflecting that of historical observations (e.g., El Nino and La Nina like features) (Cayan et al. 2008). For the future climate cases, output from the same model's SRESA2(run1) case was used. In California, the GFDL GCM produces larger temperature increases under future greenhouse gas concentrations than the PCM model, but smaller increases than HadCM3, all three of which were used in the 2006 Climate Action Team Report prepared for the state of California (Climate Action Team 2006). Precipitation projections did not change substantially from historic levels, with the GFDL A2 scenario 10-20% drier in Northern California, with a tendency for more large precipitation events and little change in the frequency of El Nino type conditions (Cayan et al. 2008). This GCM was chosen for the present study because the 6-hourly output was readily available for relevant cases and output from this model had been used to drive the vegetation model that provided our vegetation scenarios. Therefore, the climate and vegetation forcings are consistent.

2.3. Vegetation Datasets and Parameterizations

2.3.1. Native Vegetation Distribution

The Historic Native and Future Native vegetation cases were derived from the MC1 DVM described in Lenihan et al. (2008). MC1 uses monthly climate data to simulate exchanges of carbon, nitrogen and water within ecosystems, fire responses, and the mixtures of plant types that occur together in a given grid cell. Previously published vegetation distributions produced by MC1, which had been run with monthly climate variables for the period 1895-2099, were used: a Historic Native vegetation distribution was obtained from the 1961-1990 modal values for each grid cell, and a Future Native vegetation distribution was obtained from the 2070-2099 modal values for each grid cell. Future climate variables were based on the GFDL A2 scenario (see Lenihan et al. 2008 for details). As mentioned above, MC1 predicts increases in the area covered by desert, grassland, and mixed evergreen forest at the expense of conifer forest and alpine/subalpine forest categories under the A2 scenarios (Figure 1).

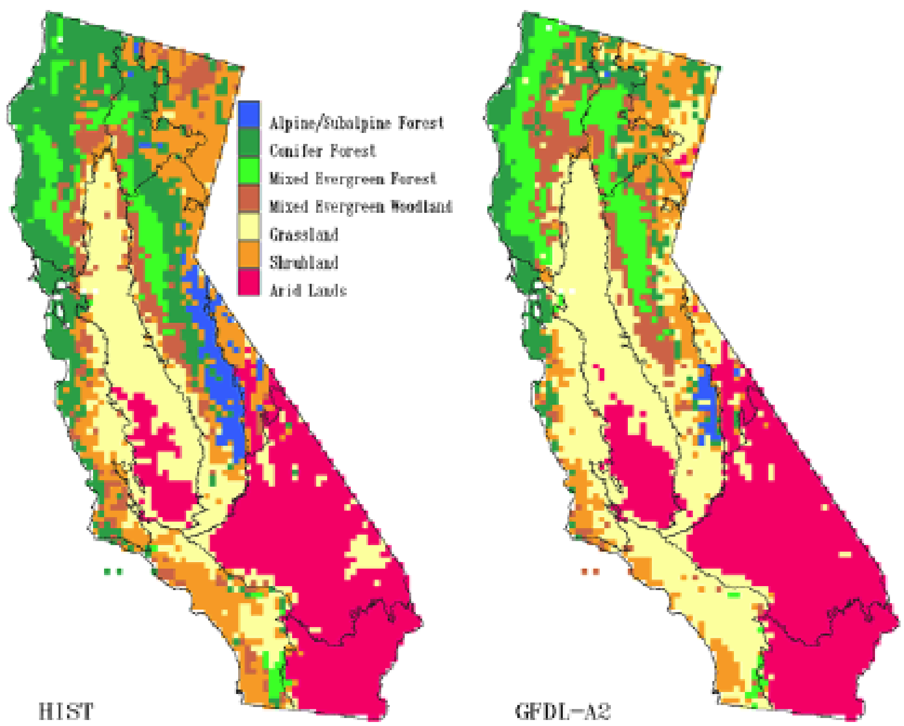
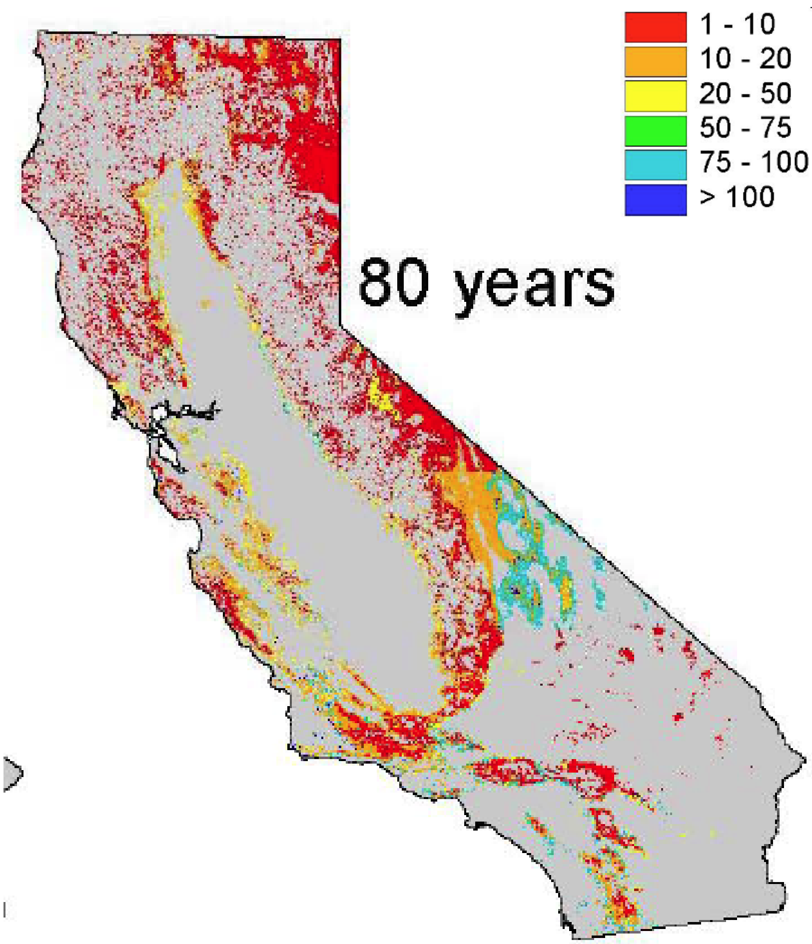


Figure 1. **Vegetation distributions from Lenihan et al. (2008) used in the Historic Native (left) and Future Native (right) cases. Reproduced from Lenihan et al. (2008) Figure 3.**

2.3.2. Afforestation Scenario

To represent potential changes in vegetation distribution as a consequence of deliberate afforestation to mitigate carbon dioxide emissions, an analysis by Brown et al. (2004) delineating areas that met criteria for afforestation was used, and within that area grid cells dominated by non-tree vegetations types were modified to be continental temperate coniferous forest. Brown et al.'s scenario was a spatially explicit afforestation scenario that identified areas with < 40% canopy cover that would be suitable for enhanced tree cover according to historical climate, soil, and other biophysical factors. The scenario further limited afforestation areas to those where the costs (including opportunity costs) of converting the rangeland to a carbon forest were economically advantageous on an 80-year time horizon, under a range of carbon prices (Figure 2). Areas deemed suitable excluded agricultural, urban and wetland areas. According to this analysis, after 80 years, 1,501 million tones of carbon could be sequestered on 9.2 million hectares of land for $20 or less (Brown et al. 2004).

Figure 2. Rangeland areas suitable for afforestation color coded by cost ($/t C) at 80 years from Brown et al. (2004).



2.3.3. California-Specific Plant Functional Types (PFTs)

New PFTs for California were defined with guidance from several California natural history texts (Barbour and Majors 1988, Schoenherr 1992, Ornduff et al. 2003), with the goal of differentiating plant types by physiology, physiognomy, life history and phenology. Sixteen PFTs were identified that captured the major dominant species types in California (Table 2).

Table 2. California-specific plant functional types created in CLM3 and examples species.

California PFT (code)	Major species	Other components
Temperate evergreen conifer (TEGC)	Douglas fir Sugar pine White fir Incense cedar	Red fir Coulter pine Grey or Foothill Pine
Fire-dependent evergreen conifer (FIDC)	Ponderosa pine	
Fog-dependent evergreen conifer (FODC)	Coast redwood Western Red Cedar	
Cold hardy evergreen conifer (CHEGC)	Lodgepole pine Whitebark Foxtail pine Mountain hemlock	
Broadleaf evergreen tree (BLEG)	Canyon live oak Interior live oak Coast live oak	California laurel Tanbark oak Madrone Golden chinquapin
Cold deciduous broadleaf tree (CDBT)	Blue oak Valley oak	Black oak California walnut Western redbud
Drought deciduous broadleaf tree (DDBT)	California buckeye Palo verde	Blue palo verde Smoketree
Drought-deciduous shrub (DDS)	White bur sage	Buckwheat Brittle bush California buckwheat Black sage White sage Bitterbrush
Xeromorphic evergreen shrub (XEGS)	Creosote bush Chamise	Manzanita Ceanothus Big sagebrush
Evergreen shrub (EGS)		Whiteleaf manzanita Mountain misery Ceanothus spp. Mountain mahogany California flannelbush Toyon Hollyleaf cherry Woolly blue curls
Cold deciduous shrub (CDS)	Greasewood Deerbrush	Currant spp.
Perennial bunchgrass (C3) (PGC3)	Needlegrass Speargrass	Blue wheatgrass Pine bluegrass Idaho fescue
Annual grass (C4) (AGC4)	Species not identified	

Succulents/cactus (SUC)	Prickly pear Chaparral yucca	Compass barrel cactus Ocotillo Silver cholla Diamond cholla Devil's cholla
Herbaceous plants (HP)		Many
Wetland monocots (WM)		Common tule California bulrush Olney bulrush Tule Cattaill Soft flag

To translate the vegetation distributions utilized in MC1 into combinations of the PFTs created for CLM3, the Kuchler (1975) U.S. potential vegetation classification was used. The Kuchler classification, a qualitatively derived dataset that considers only potential vegetation, not actual vegetation, is described by combinations of dominant and "other component" or common species. Each of these species was matched to one of the 16 PFTs defined for this study. Then the total fraction (by area as seen from space) of dominant species, common species, and bare ground during the growing season was assigned (these three fractions sum to one) for each Kuchler vegetation type. The bare ground fraction loosely follows the bare ground fractions for PFTs reported in Bonan et al. (2002a) and is additionally based on Kuchler's descriptions (Kuchler 1964), CNPS-CDFG Vegetation Mapping protocols (Keeler-Wolf et al. Pers. Comm.), and personal observations (by D. Svehla). The last three knowledge bases also guided the determination of the total dominant and common species fractions, since the Kuchler vegetation types were not quantitatively defined in terms of species fractions. These species fractions were then converted to PFT fractions, accordingly. Finally, the Kuchler vegetation types (and associated PFT fractions) were aggregated into the MC1 vegetation classes according to the scheme used by Lenihan et al. (2008), weighting the Kuchler types (and PFT fractions) according to their area in California using a digitized version of Kuchler's 1975 U.S. potential vegetation map (Table 3).

Table 3. **PFT combinations, including bare ground (BG) and water (W) for MC1 vegetation types that appear in California, and associated Kuchler types.**

California PFT fractions	MC1 vegetation type	Kuchler vegetation types
25% PGC3; 23% HP; 0.03 CDS; 50% BG	Tundra	Alpine meadows and barren
70% CHEGC; 4% HP; 1% CDS; 25% BG	Boreal forest*	Lodgepole pine-subalpine forest
53% TEGC; 18% FODC; 6% CDS; 23%BG	Maritime temperate coniferous forest	Cedar-hemlock-douglas fir forest Mixed conifer forest Redwood forest Pine- cypress forest
40% TEGC; 25% FIDC; 17% EGS; 18% BG	Continental temperate coniferous forest	Red fir forest Ponderosa shrub forest Great basin pine forest

56% BEGT; 11% CDBT; 8% TEGC; 25% BG	Warm temperate/subtropical mixed forest	California mixed evergreen forest
37% BEGT; 21% CDBT; 17% TEGC; 26% BG	Temperate mixed xeromorphic woodland	California oak woods California oak woods – Coastal sagebrush mosaic
36% TEGC; 15% EGS; 9% PGC3; 40% BG	Temperate conifer xeromorphic woodland	Juniper-pinyon woodland
32% XEGS; 28% PGC3; 15% TEGC; 25% BG	Temperate conifer savanna	Juniper steppe woodland
31% PGC3; 28% AGC4; 11% HP; 30% BG	C3 grassland†	Fescue-oatgrass California steppe
40% AGC4; 10% PGC3; 10% HP; 40% BG	C4 grassland†	
40% XEGS; 16% EGS; 9% DDS; 34% BG	Mediterranean shrubland	Chaparral Montane chaparral Coastal sagebrush
20% XEGS; 8% PGC3; 4% HP; 68% BG	Temperate arid shrubland	Great basin sagebrush Saltbrush-greasewood Sagebrush steppe Desert: Vegetation largely absent
13% XEGS; 6% DDS; 2% SUC; 78% BG	Subtropical arid shrubland	Creosote bush Creosote bush – bur sage Palo verde – cactus shrub
50% WM; 10% BG; 40% W	Wetland	Tule marshes

* Lenihan et al. 2008 do not have explicit Kuchler vegetation assignments to their Boreal forest vegetation type; the Lodgepole pine-subalpine forest was used for the relevant type for California, and for assigning PFT fractions

† Lenihan et al. 2008 separately represent C_3 and C_4 grassland types, while in CLM3 "Mixed grassland" and "C_4 dominated grassland" both were represented as mixtures of C_3 perennial and C_4 grasses. C_4 dominated grasslands were not present in the Kuchler vegetation classes.

2.3.4. Plant Functional Type Parameters

PFT parameter values for the 16 new California PFTs were derived from published literature, remotely sensed datasets, or similar preexisting CLM3 PFTs (Table 4). Efforts were made to use values for the dominant species in each PFT, weighted if possible by the fraction of the PFT that the species comprises. For PFT parameters for which no data were found, values for the most similar PFT were used. In some cases, parameters from the default PFT types were retained for similar new PFTs (e.g., canopy height of some tree PFTs, stem area index).

Monthly leaf area index (LAI) for each California PFT was determined using MODIS 16-day LAI values (August 2004 – July 2005) masked using the California Gap Analysis vegetation cover type database (Davis et al. 1998), which had been interpolated to a common 1 km pixel resolution. For example, to determine the monthly LAI sequence for fire-dependent evergreen conifer, MODIS pixels overlapping the Gap Analysis pixels identified as Coast Range Ponderosa Pine Forest, Westside Ponderosa Pine Forest, Eastside Ponderosa Pine Forest, and Big Tree Forest were averaged. The resulting annual cycles of LAI values were determined to be reasonable.

Table 4. Parameter values used in CLM3 to represent new California specific PFTs. Not all PFTs were represented in the model domain.

PFTs	canopy top (z_{top}; m)	canopy bottom (z_{bot}; m)	Leaf orientation (X_L; +1 = horizontal, 0 = random, -1 = vertical)	α leaf VIS	α leaf NIR	α stem VIS	α stem NIR	τ leaf VIS	τ leaf NIR	τ stem VIS	τ stem NIR	Characteristic dimension of leaves in direction of wind flow (d_{leaf}; m)	Momentum roughness length ratio to canopy heigh (R_{zOm})	Displacement height ratio to canopy top height (R_d)	root distribution parameter (r_a)	root distribution parameter (r_b)	Max rate of carboxylation @ 25C (V_{max25}; µmol $CO_2/m^2/s$)	Quantum efficiency (α; µmol CO_2/µmol photon)	PFT empirical parameter = slope of conductance-to-PS relationship (m)	photosynthetic pathway (C3 or C4)
temperate evergreen conifer	17	8.5	0.01	0.07	0.45	0.16	0.39	0.05	0.1	0.001	0.001	0.04	0.14	0.75	7	2	43	0.06	6	C3
fire-dependent evergreen conifer	17	8.5	0.01	0.07	0.35	0.16	0.39	0.05	0.1	0.001	0.001	0.04	0.13	0.67	7	2	52	0.06	6	C3
fog-dependent evergreen conifer	17	8.5	0.01	0.07	0.35	0.16	0.39	0.05	0.1	0.001	0.001	0.04	0.03	0.84	7	2	36	0.06	6	C3
cold hardy evergreen conifer	17	8.5	0.01	0.07	0.35	0.16	0.39	0.05	0.1	0.001	0.001	0.04	0.05	0.76	7	2	43	0.026	6	C3
broadleaf evergreen tree	35	1	0.1	0.1	0.45	0.16	0.39	0.05	0.25	0.001	0.001	0.04	0.075	0.67	7	1	69	0.06	9	C3
cold deciduous broadleaf tree	20	11	0.25	0.1	0.45	0.16	0.39	0.05	0.25	0.001	0.001	0.04	0.13	0.67	6	2	127	0.06	8	C3
drought deciduous broadleaf tree	20	11	0.25	0.1	0.45	0.16	0.39	0.05	0.25	0.001	0.001	0.04	0.13	0.67	6	2		0.06	9	C3
drought-deciduous shrub	1	0	0.25	0.2	0.6	0.16	0.39	0	0	0.001	0.001	0.04	0.12	0.68	7	1.5	182	0.06	9	C3
Xeromorphic evergreen shrub	2	0.5	0	0.1	0.5	0.16	0.39	0.01	0.01	0.001	0.001	0.04	0.12	0.68	7	1.5	100	0.02	9	C3
evergreen shrub	0.5	0.1	0.01	0.1	0.45	0.16	0.39	0.05	0.25	0.001	0.001	0.04	0.12	0.68	7	1.5	17	0.06	9	C3
deciduous shrub	0.5	0.1	0.25	0.1	0.45	0.16	0.39	0.05	0.25	0.001	0.001	0.04	0.12	0.68	7	1.5	17	0.06	9	C3
perennial bunchgrass (C3)	0.5	0.01	-0.3	0.11	0.58	0.36	0.58	0.07	0.25	0.22	0.38	0.04	0.15	0.57	11	2	75	0.06	9	C3
annual grass (C4)	0.5	0.01	-0.3	0.11	0.58	0.36	0.58	0.07	0.25	0.22	0.38	0.04	0.12	0.68	11	2	24	0.04	5	C4
succulents/cactus (CAM)	10	0	-0.3	0.3	0.7	0.36	0.58	0	0	0.22	0.38	0.04	0.12	0.68	11	2	24	0.04	5	C3
herbaceous plants	0.5	0.01	-0.3	0.11	0.58	0.36	0.58	0.07	0.25	0.22	0.38	0.04	0.12	0.68	6	3	50	0.06	9	C3
wetland monocots	1.5	0.01	-0.3	0.11	0.58	0.36	0.58	0.07	0.25	0.22	0.38	0.04	0.12	0.68	11	2	50	0.06	9	C3

2.4. Data Analysis

The final ten years (January-December) of the thirteen-year simulations was analyzed, leaving the first three years for model equilibration. The analysis presented here focuses on ten-year averages of monthly mean, maximum (4 PM), and minimum (4 AM) values of primary climate and energy budget variables at the surface. Results for California as a whole and for two specific vegetation transitions within subregions of California are presented to illustrate the study's findings. The statistical significance of results was evaluated with a paired t-test at the grid cell level; all temperature differences greater than 0.3 degrees were significant at the 95% confidence level.

3.0 Results and Discussion

3.1. Do Shifts in Native Vegetation with Climate Change Amplify (or Diminish) Climate Change in California?

3.1.1. Climate Change Impacts in California in the Absence of Vegetation Changes

In the absence of vegetation change, California regional climate warms substantially between scenarios with historical climate and vegetation (HCHV) and future (A2) climate and historical vegetation (FCHV) (Figure 3). These estimates are statistically significant throughout the domain at the 95% confidence level and are broadly consistent with estimates in Hayhoe et al. (2004) and Cayan et al. (2008) based on the same future emissions scenario and GCM. Temperature increases are more pronounced in the Sierra Nevada than along the coast, and in the North than in the South. The largest changes occurred midday in the summer, with values up to 10 °C warmer in parts of Northern California and the Sierra Nevada. Finally, the maximum temperature was more sensitive to the climate forcing than was the minimum temperature.

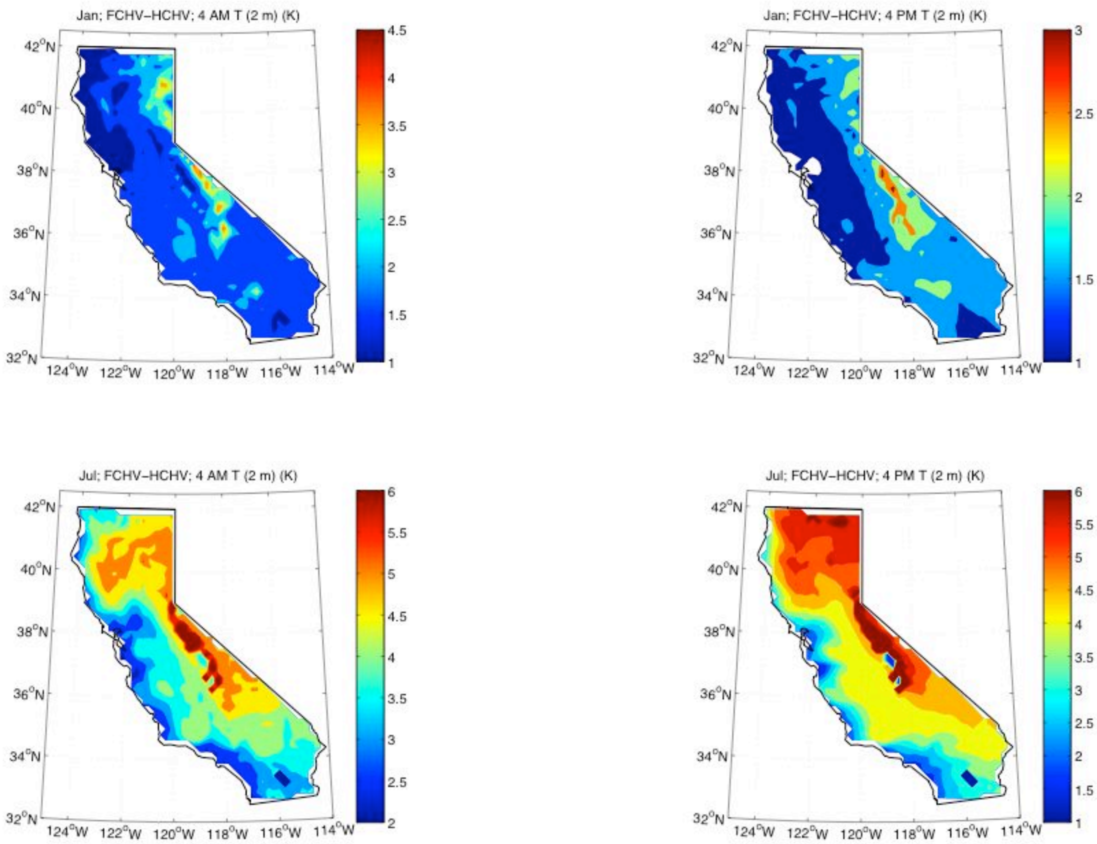


Figure 3. Differences between future and historical climate (both with historical vegetation) 2 m monthly mean 4 AM and 4 PM temperatures for January and July (FCHV-HCHV). All changes are statistically significant at the 95% confidence level.

3.1.2. Effects of Vegetation Changes on Regional Climate

The effects of vegetation change alone on climate were estimated as the difference between the future climate future vegetation (FCFV) and FCHV model simulations. In these two simulations, climate boundary conditions were the same, but the distribution of ecosystem types was changed according to the projections of the MC1 dynamic vegetation model (Figure 4). Two significant ecosystem conversions are the mixed grassland to C_4-dominated grassland transition in the northern Central Valley (R1), and the continental temperate coniferous forest to warm temperate/subtropical mixed forest and temperate mixed xeromorphic woodland transition in the northern part of the state (R2). For the analyses that follow, these two regions are defined as the set of grid cells within each spatial domain with these specific changes in vegetation cover.

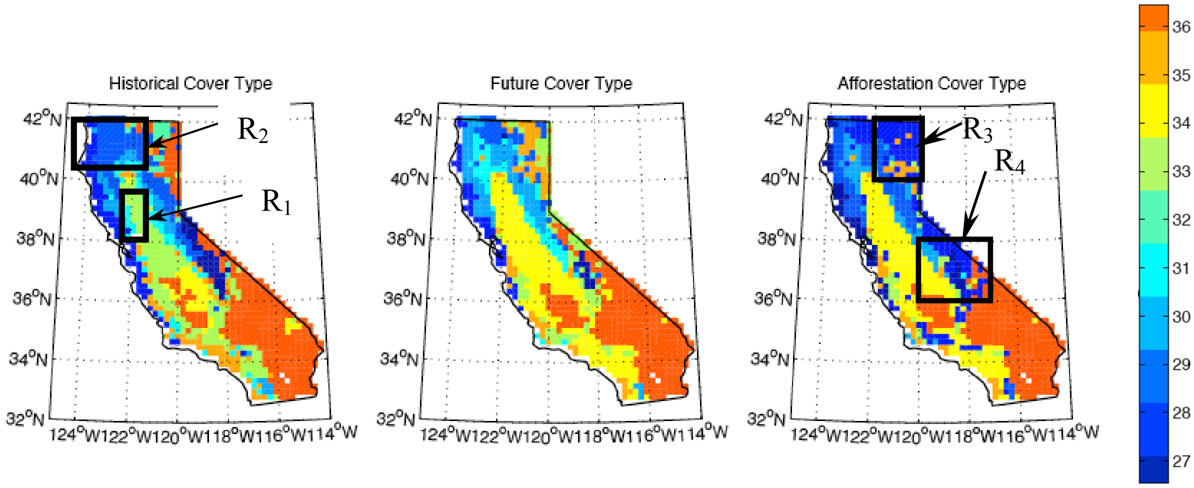


Figure 4. Vegetation for historical (HV), future (FV), and future + afforestation (AV) cases. In the left panel, subregions R1 and R2 are outlined, while in the right panel subregions R3 and R4 are outlined. The cover type labels correspond to: Tundra = 25; Boreal Forest = 26; Maritime Temperate Coniferous forest = 27; Continental Temperate Coniferous forest = 28; Warm Temperate/Subtropical Mixed forest = 29; Temperate Mixed Xeromorphic woodland = 30; Temperate Conifer Xeromorphic woodland = 31; Temperate Conifer Savanna = 32; C_3 Grassland = 33; C_4 Grassland = 34; Mediterranean Shrubland = 35; Temperate Arid Shrubland = 36; Subtropical Arid Shrubland = 37; Wetland = 38.

The effect of change from the historical (HV) to future (FV) vegetation scenarios on 2 m air temperatures was statistically significant at the 95% confidence level in much of the domain, but varied from positive to negative across the state, rendering statewide averages of temperature changes associated with vegetation shifts unhelpful (Table 5). However, the signs of the temperature changes were consistent throughout the year, with the most pronounced differences in summer (Figure 5). January midday and nighttime 2 m air temperature changes were small (Table 5). However, July midday 2 m temperatures increased by ~1.1 °C in R1 and decreased by ~ -0.7 °C in R2.

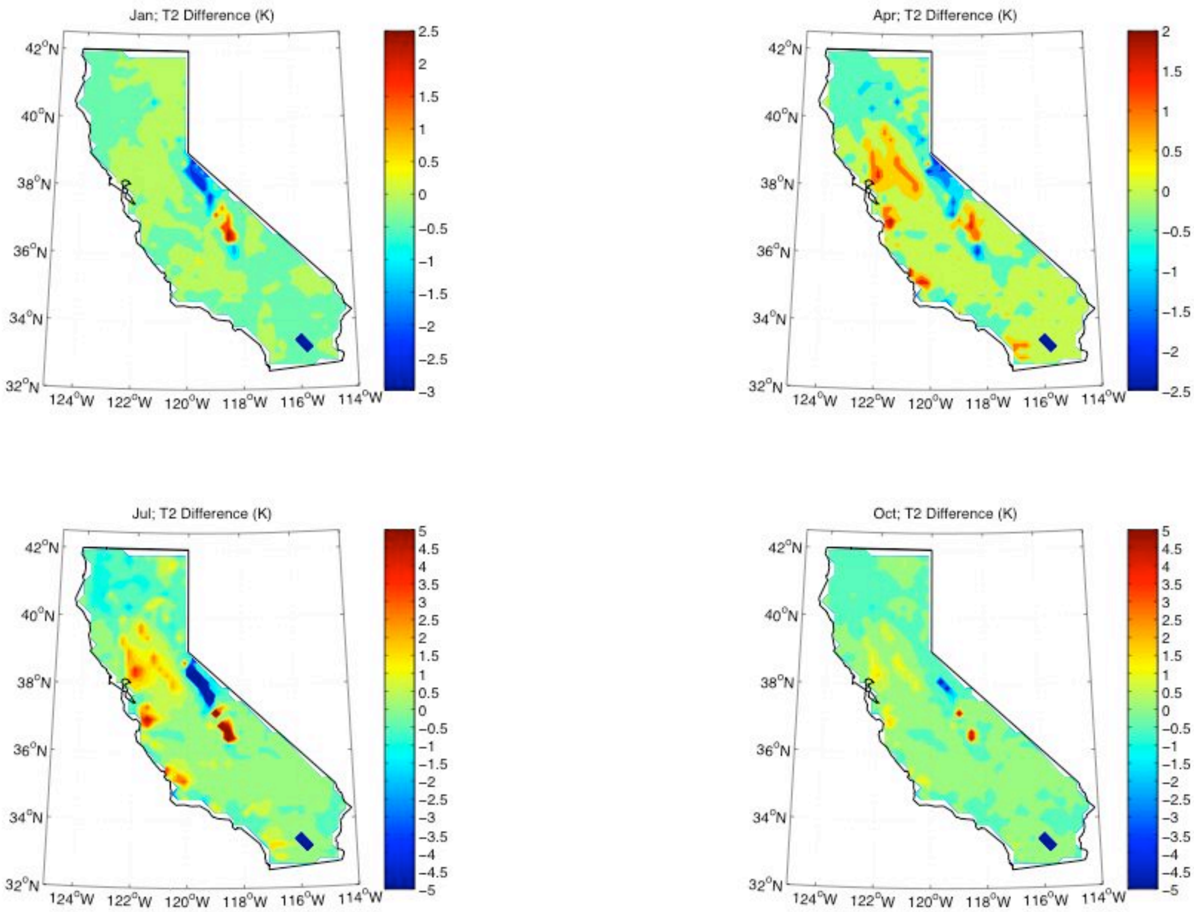


Figure 5. Monthly averaged 4 PM 2 m air temperature differences between the FCFV and FCHV scenarios for January, April, July, and October. The decline in annual-averaged 4 PM temperature in the northwestern part of the state occurred in each month. However, the increases in temperature in the northern Central Valley were less evident in January, and most pronounced in July. Temperature differences greater than 0.07K for Jan, than 0.11 for Apr, than 0.13K for Jul, and than 0.05 for Oct are statistically significant at the 95% confidence level.

The annual average 2 m air temperature difference (Figure 6) also shows an area of strong cooling in a patch of the northwestern Sierras and an area of strong warming to the southeast; the cooling area also shows an increase in annual average snowcover of several meters, while the opposite is true in the warming area. These dynamics illustrate how the snow-albedo feedback can greatly amplify the effects of vegetation change on the local temperature. Because of this strong amplification, it is difficult to pinpoint the initial change responsible, but one possible explanation is that an advance of forest into higher altitude in the southeast region contrasted with a shift from dark Boreal (subalpine) forest to lighter Temperate (montane) forest in the northwest region.

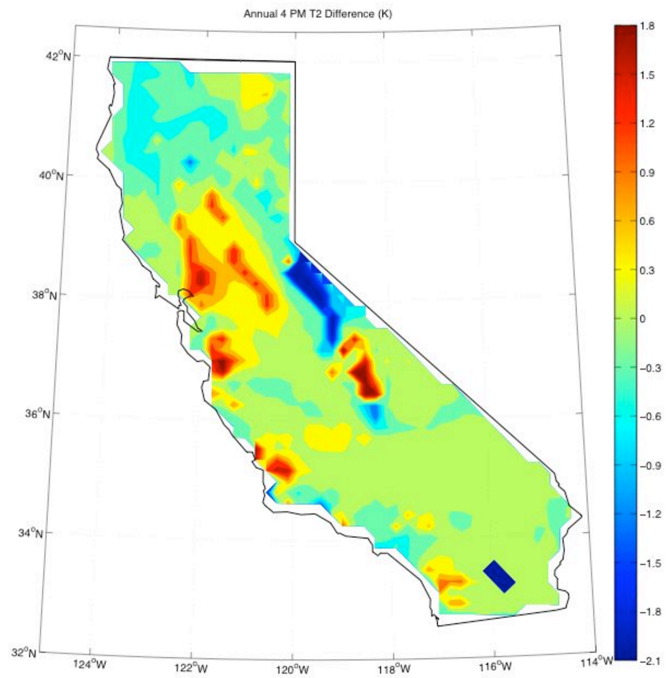


Figure 6. Annual Average 4 pm 2 m air temperature difference between the future and historical vegetation cases, with climate boundary conditions held constant (FCFV-FCHV) under the A2 scenario. Temperature changes greater than 0.2K were statistically significant at the 95% confidence level.

Table 5. Difference in 4 pm 2 m air temperature between historical and future vegetation cases with climate boundary conditions held constant under the future (A2) climate scenario (FCFV-FCHV).

	Mean Annual Difference (°C)	*Mean January Difference (°C)*	*Mean July Difference (°C)*
California	0.1	0.0	0.2
R1	0.5	0.0	1.1
R2	-0.4	-0.1	-0.7

3.1.3. Combined Climate and Vegetation Change

The overall predicted change in statewide temperatures as a consequence of both large-scale (global) climate forcing and regional vegetation change (calculated as FCFV-HCHV) was large (Figure 7; Table 6). In July, midday temperature was more sensitive to the combined climate and vegetation changes than was the minimum temperature, while in January the minimum temperature was more sensitive. Averaged across the state, January and July 2 m air temperatures increased ~2 and 5 °C, respectively. The largest increases in July temperature occurred in the Northern part of the state.

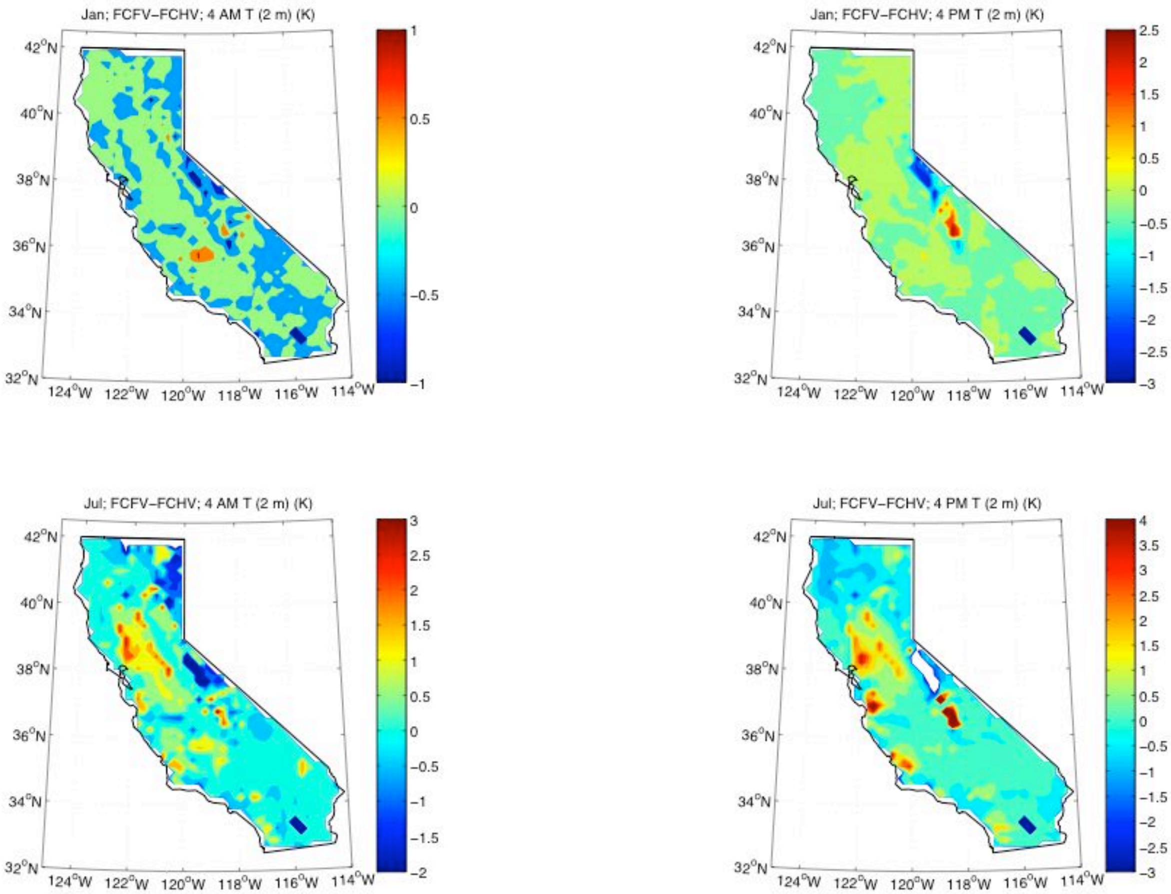


Figure 7. 4 AM and 4 PM 2 m air temperature differences between FCFV and HCHV for January and July. All temperature differences are statistically significant at the 95% confidence level.

Table 6. 4 AM and 4 PM mean annual, January, and July temperature differences across California with both large-scale climate and regional vegetation change (FCFV-HCHV).

	Mean Annual Difference (°C)	*Mean January Difference (°C)*	*Mean July Difference (°C)*
California (4 AM)	3.2	1.9	4.5
California (4 PM)	3.2	1.6	4.7

A key question of this study is whether changes in regional vegetation distribution with climate change have the potential to significantly alter projections of regional (i.e., California's) climate, which typically are based only on global-scale forcings (i.e., increasing global trace gas concentrations). The relative importance of these vegetation feedbacks in California was estimated as the ratio between climate change due to vegetation change alone and climate change due to both vegetation change and large-scale forcing (FCFV-FCHV)/(FCFV-HCHV) (Figure 8).

Across California, the model simulations suggest that up to 60% of total projected temperature change in snow-free regions under an A2 scenario could come from expected changes in vegetation, with large variations depending on the region and time of year. Vegetation forcing appears to be relatively more important in spring through fall, and less important in winter, for relatively snow-free regions. Vegetation change also has a relatively more important contribution to temperature change where the conversion between ecosystems is more dramatic. For example, both July and October relative changes are large in the two subregions described earlier (R1 and R2).

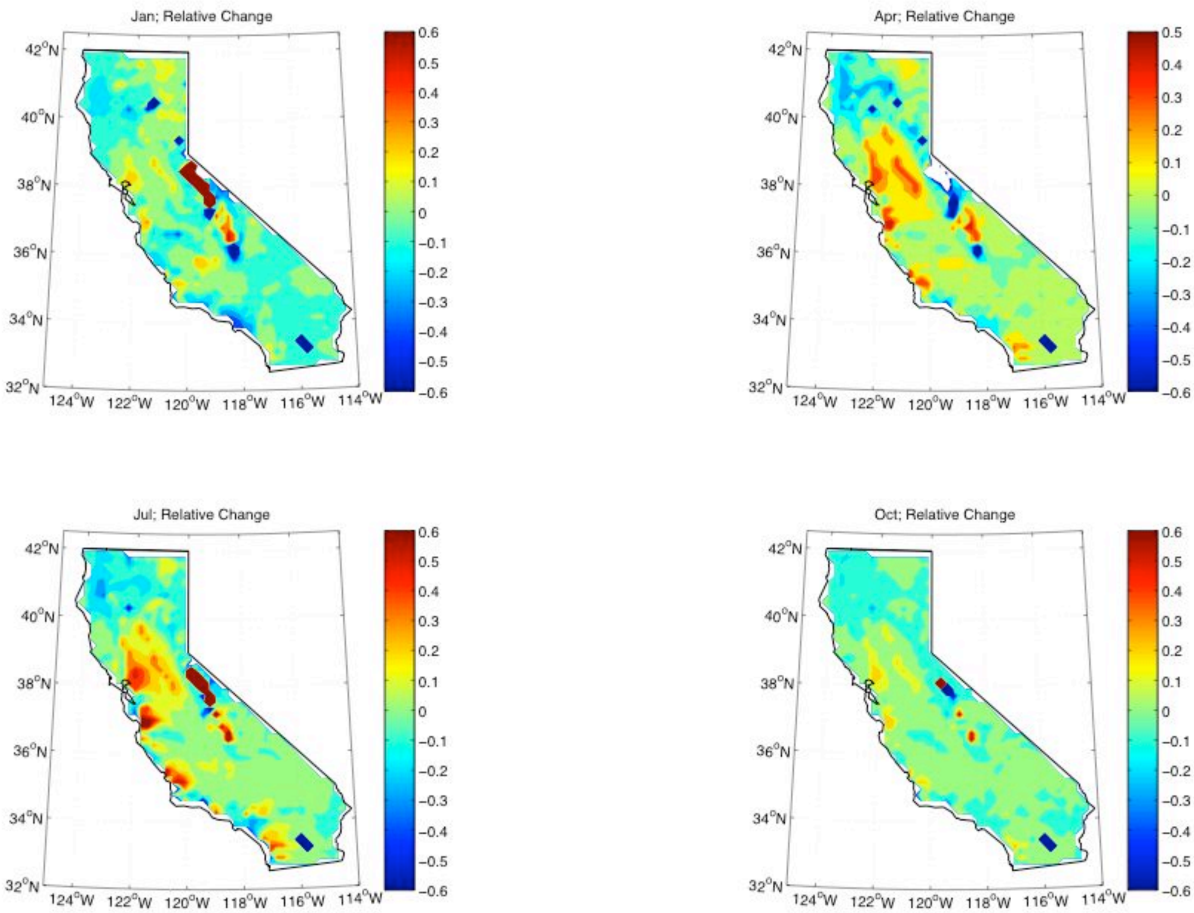


Figure 8. Impact of vegetation changes alone relative to changes in both climate and vegetation on 4 PM surface air temperature (FCFV-FCHV)/(FCFV-HCHV).Large relative changes occur in the northern Central Valley (positive) and northwestern corner of the state (negative).

3.2. Why is Vegetation Change an Important Part of Regional Temperature Change?

To better understand the factors driving the changes in temperature as a consequence of vegetation change, energy, water, and atmospheric variables for R1 and R2 during July (which had relatively large differences) were examined. In R1, the Central Valley north of the San Francisco Bay and Sacramento, the largest differences in midday temperatures were associated with a relatively widespread shift from a mixed grassland (with a large component of perennial C_3 grasses) to a C_4 dominated grassland (with larger fractions of annual C_4 grasses and bare ground) (Table 3; Figure 9).

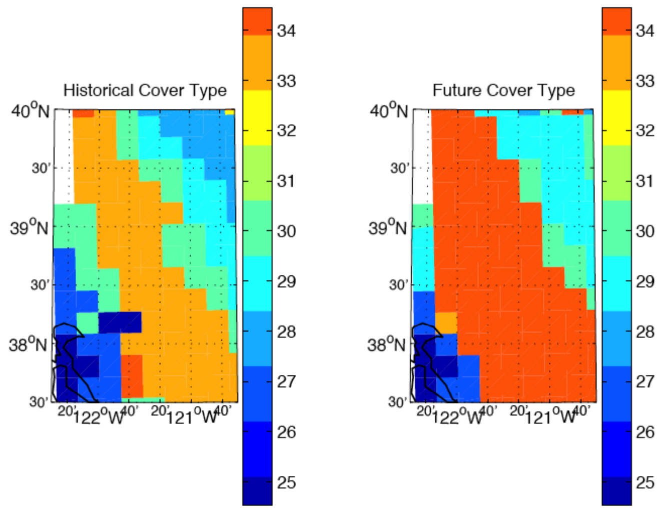


Figure 9. Historical and future land cover types in R1, the region north of Sacramento and the San Francisco Bay.

During July in R1 where the grassland transition occurred, regional average (1) shortwave albedo decreased by 0.01; (2) latent heat (LH) fluxes decreased 3 W m^{-2}; (3) sensible heat (SH) fluxes decreased 3 W m^{-2}; and (4) longwave upward (LW up) fluxes increased by 9 W m^{-2} (Figure 10, Table 7). There were also large changes in horizontal wind speed in parts of the region, although the regional average change was small (0.05 m s^{-1}). These preliminary results suggest that, in R1, the air temperature response to changing vegetation was caused by a slightly greater absorption of incoming short wave radiation, lower heat loss via latent and sensible heat fluxes, and greater upward long wave radiation fluxes.

The second subregion examined, R2 (continental temperate coniferous forest transition to warm temperate/subtropical mixed forest and temperate mixed xeromorphic woodland transition in the northern part of the state), responded to changing vegetation opposite to the changes in R1 (Table 7). Here, the temperature decreased as a result of the changing vegetation, with relatively larger changes to the latent and sensible heat budgets (23 and -40 W m^{-2}, respectively) and to the LW up flux (-10 W m^{-2}). It is hypothesized that the large decreases in sensible heat flux and LW up flux accounted for the decrease in average July 2 m air temperature. Other changes within the planetary boundary layer resulting from the changes in the surface energy budget (e.g., wind speed, humidity, PBL dynamics) could have important impacts on near-surface air temperatures, and will be investigated in future work.

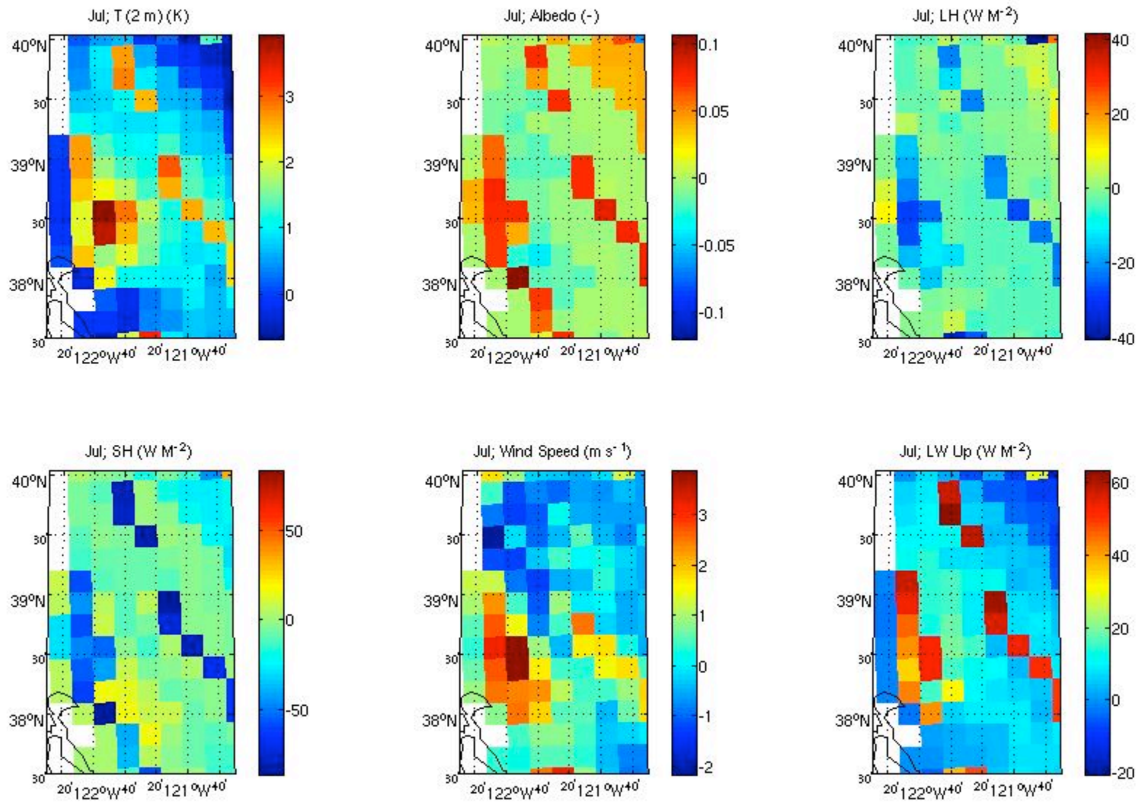


Figure 10. First row: 2 m air temperature; albedo; latent heat. Second row: sensible heat; wind speed; and longwave upward flux. All quantities are average differences under future climate between future and historical cover types in R1 at 4 PM in July (FCFV-FCHV).

Table 7. July 4 PM differences in energy budget variables between future and historical vegetation cases both under future climate (FCFV-FCHV) for R1 and R2.

	Albedo (fraction)	*LH (W m^{-2})*	*SH (W m^{-2})*	*LW up (W m^{-2})*
R1	-0.01	-3	-3	9
R2	0.04	23	-40	-10

3.3. Effects of Native Vegetation Change and Afforestation on California Climate

As an initial estimate of the effect of afforestation on regional climate, two regions where afforestation occurred over relatively large areas were considered: The northeastern corner of the state (R3) and the Sierra and its foothills (R4) (Figure 4). The dominant cover type change in both regions was from shrubland to coniferous forest. Table 8 shows mean annual, January, and July midday 2 m temperature differences for each region, averaged across all the grid cells in the region where afforestation occurred. The largest differences were in July in R3, with changes in temperature associated with afforestation (as compared to the future vegetation case) of -1.8; in R4 the largest change occurred in January, increasing 0.6 °C suggesting warming associated with a snow-albedo feedback.

The area showing decreases in temperature (cooling) is very broad; the entire state annual average temperature decreased by 0.1 ºC. The area showing a temperature increase is relatively compact and also showed a sharp decrease in snow cover: several meters in annual average snow cover in some places. One explanation for the contrasting behavior is that this area is of marginal snow cover, so that a decrease in albedo at certain times of the year induces a snow-albedo feedback that overwhelms the cooling effect that the vegetation change causes elsewhere. Whether this effect would be experienced on a significant scale in this region depends on whether regions of afforestation are indeed with marginal snow cover; WRF-CLM under- and overestimates snow at different times of the year in the Sierras, and may be under- or overestimating the scale of such an effect.

The predicted decrease in temperature for regions of non-marginal snow cover is in contrast to a previous study (Gibbard et al. 2005), which found that the decrease in albedo associated with reforestation dominated and led to predicted net warming of the near-surface atmosphere, but is somewhat consistent with other land cover sensitivity experiments which have found cooling (warming) in summer months and/or warming (cooling) in winter with the addition (removal) of forest (Jackson et al. 2005, Snyder et al. 2004). The mechanisms responsible for the range of responses include decreased albedo increasing the total radiation, increased evapotranspiration, changes in snow cover, and changes in surface long wave fluxes. The complex trade-offs among changes in albedo, transpiration, soil evaporation, and long-wave radiation fluxes and the resulting effects on boundary layer properties warrant further research, particularly in light of policies promoting afforestation as a partial remedy for anthropogenic climate change. Further, from a practical perspective, this study prescribed forest in many areas that MC1 projected to be occupied by grassland, shrubland, or woodland under future climate (Figure 4), and may therefore be unable to support new forest in 100 years or less. Additional studies of afforestation potential should incorporate climate change itself into characterization of suitable sites, and consider local and regional climate feedbacks from tree planting, particularly in the context of present and future snow cover.

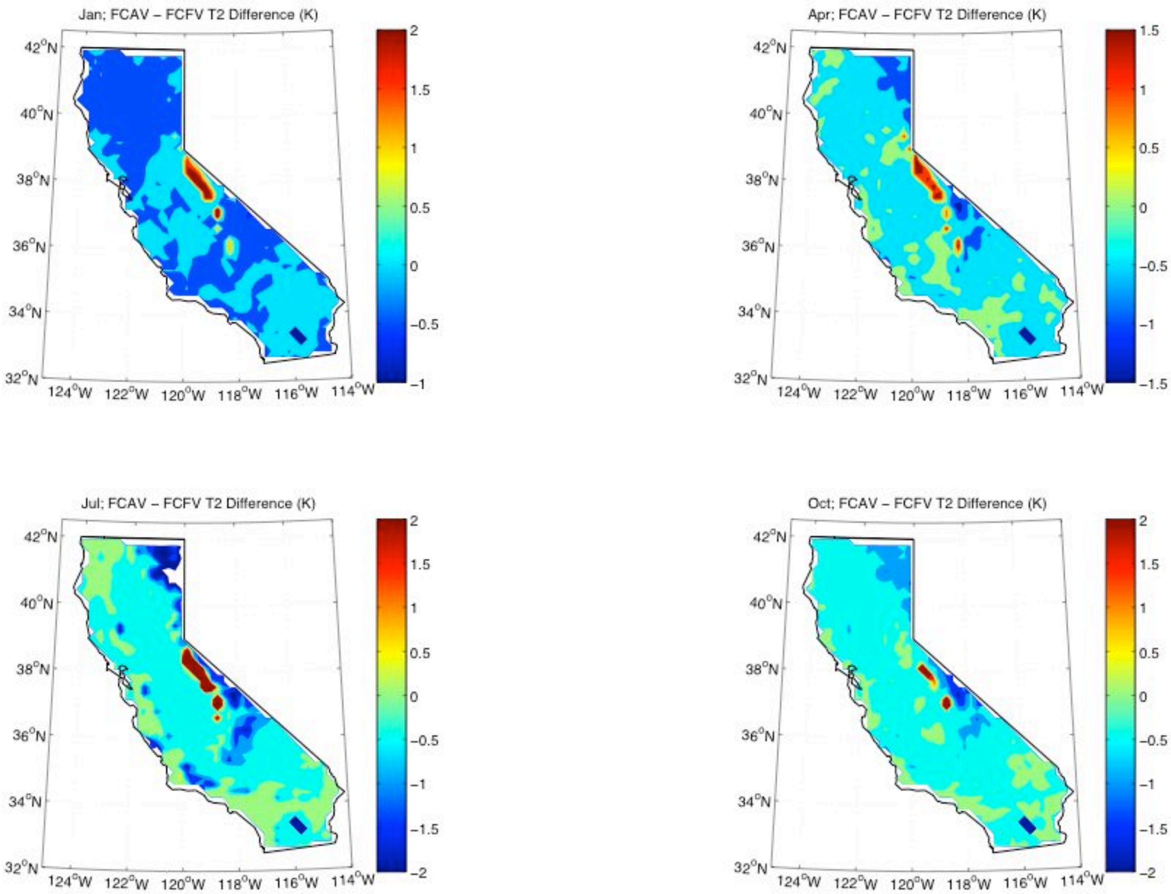


Figure 11. Difference in 2 m 4 pm air temperatures between future native and future native + afforestation vegetation cases with climate boundary conditions under the future (A2) climate scenario (FCAV-FCFV). Significant broad cooling occurs statewide, except for a region of marginal snow cover in the Sierras where the lower albedo forest decreases snow cover, causing the warming effects to dominate. Temperature differences greater than 0.05 for Jan, than 0.06 for Apr, than 0.10 for Jul, and than 0.04 for Oct are statistically significant at the 95% confidence level.

Table 8. Difference in 2 m air temperatures between future and afforestation vegetation cases with climate boundary conditions held constant under the future (A2) climate scenario (FCAV-FCFV).

	Mean Annual Difference (℃)	*Mean January Difference (℃)*	*Mean July Difference (℃)*
R3	-0.9	-0.03	-1.8
R4	0.1	0.6	0.4

4.0 Conclusions

In this study a state-of-the-art coupled land-surface and regional climate model was used to investigate the magnitude and consequences of climate and vegetation feedbacks. Results from the present sensitivity study based on ten-year model simulations suggest the following:

1) In the absence of vegetation change, California regional climate warms substantially between historical and future climate scenarios with constant (historical) vegetation. These projections are consistent with other recently published analyses.
2) Independent of large-scale climate change, the effect of vegetation changes on 2 m air temperatures varied from positive to negative across the state, with the most pronounced differences during summer. July midday 2 m temperatures increased by ~1.1 °C in the Central Valley north of Sacramento and decreased by ~-0.7 °C in the Northwest corner of the state.
3) The overall predicted change in regional temperatures as a consequence of both large-scale (global) climate forcing and regional vegetation change was large. Averaged across the state, January and July 2 m air temperatures increased ~2 and 5 °C, respectively.
4) Across California, the model simulations suggest that up to 60% of total projected 2 m air temperature change in snow-free regions comes from vegetation changes, with large variations depending on the region and time of year. This is a comparable effect to that found by Diffenbaugh (2005) using a different model configuration. This estimate may be conservative due to the small size of the model domain and the potential for influence of the large-scale climate in the interior of the domain where land cover changes were made.
5) A complex set of changes in radiation, mass, and energy budgets associated with vegetation changes in the two regions studied led to very different changes in near-surface air temperatures. Further work is required to mechanistically explain these different climate responses.
6) Average midday air temperature differences in July between future vegetation and future vegetation + afforestation were between -0.5 and -2 °C in regions of non-marginal snow cover, except one area in the Sierra foothills where decreased snow cover caused a temperature increase. This widespread cooling effect of afforestation in California is consistent with some, but contrasts with other previous studies of temperate afforestation and deforestation. Further work is required to mechanistically explain these varied responses.

In summary, there is a significant potential for vegetation feedbacks to climate change and for afforestation-associated climate change within some areas of California. The estimates from this sensitivity study would benefit from further improvements to the regional climate model system, including development of the dynamic vegetation module for use with the California-specific PFTs. Additional model experiments of longer duration would also enable characterization of the role of vegetation change in extreme climate events (e.g., heat waves) and how various afforestation scenarios affect local climate. Finally, field measurements to verify both the magnitude of vegetation effects and the mechanisms by which they influence local and regional climate would increase confidence in these and related model results.

5.0 References

Barbour M.G. and J. Major, Eds., 1988. Terrestrial Vegetation of California, University of California Press: Berkeley, CA.

Bell, J. L., and L. C. Sloan. 2006. CO2 sensitivity of extreme climate events in the Western United States. Earth Interactions 9:Paper No. 15.

Bonan G.B., S. Levis, L. Kergoat, and K.W. Oleson, 2002a. Landscapes as patches of plant functional types: An integrating concept for climate and ecosystem models, Global Biogeochemical Cycles 16 (2), 5-1–5-18.

Bonan, G. B., K. W. Oleson, M. Vertenstein, S. Levis, X. Zeng, Y. Dai, R. E. Dickinson, and Z.-L. Yang, 2002b. The land surface climatology of the Community Land Model coupled to the NCAR Community Climate Model, J. Climate, 15, 3123-3149.

Bounoua, L., R. deFries, G. J. Collatz, P. Sellers, and H. Khan. 2002. Effects of land cover conversion on surface climate. Climatic Change 52:29-64.

Brown, S., A. Dushku, T. Pearson, D. Shoch, J. Winsten, S. Sweet, and J. Kadyszewski. 2004. Carbon Supply from Changes in Management of Forest, Range, and Agricultural Lands of California. 500-04-068F, Winrock International, for the California Energy Commission, PIER Energy-Related Environmental Research.

Cayan, D., E. P. Maurer, M. D. Dettinger, M. Tyree, and K. Hayhoe. 2008. Climate change scenarios for the California region. Climatic Change 87:S21-S42.

Climate Action Team. 2006. Climate Action Team Report to Governor Schwarzenegger and the Legislature. California Environmental Protection Agency, Sacramento.

Davis, F. W., D. M. Stoms, A. D. Hollander, K. A. Thomas, P. A. Stine, D. Odion, M. I. Borchert, J. H. Thorne, M. V. Gray, R. E. Walker, K. Warner, and J. Graae. 1998. The California Gap Analysis Project: Final Report. University of California, Santa Barbara.

DeFries, R. S., L. Bounoua, and G. J. Collatz. 2002. Human modification of the landscape and surface climate in the next fifty years. Global Change Biology 8:438-458.

Delworth, T. L., A. J. Broccoli, A. Rosati, R. J. Stouffer, V. Balaji, J. A. Beesley, W. F. Cooke, K. W. Dixon, J. Dunne, K. A. Dunne, J. W. Durachta, K. L. Findell, P. Ginoux, A. Gnanadesikan, C. T. Gordon, S. M. Griffies, R. Gudgel, M. J. Harrison, I. M. Held, R. S. Hemler, L. W. Horowitz, S. A. Klein, T. R. Knutson, P. J. Kushner, A. R. Langenhorst, H.-C. Lee, S.-J. Lin, J. Lu, S. L. Malyshev, P. C. D. Milly, V. Ramaswamy, J. Russell, M. D. Schwarzkopf, E. Shevliakova, J. J. Sirutis, M. J. Spelman, W. F. Stern, M. Winton, A. T. Wittenberg, B. Wyman, F. Zeng, and R. Zhang. 2006. GFDL's CM2 global coupled climate models. Part I: Formulation and simulation characteristics. Journal of Climate 19:643-674.

Dickinson, R. E., 1983: Land surface processes and climate-surface albedos and energy balance. Advances in Geophysics. Academic Press, 48pp.

Diffenbaugh, N. S. 2005. Atmosphere-land cover feedbacks alter the response of surface temperature to CO2 forcing in the western United States. Climate Dynamics 24:237-251.

Foley, J. A., M. H. Costa, C. Delire, N. Ramankutty, and P. K. Snyder. 2003. Green surprise? How terrestrial ecosystems could affect earth's climate. Frontiers in Ecology and Environment 1:38-44.

Gibbard S, Caldeira K, Bala G, Phillips TJ, Wickett M, 2005. Geophysical Research Letters, Vol. 32, L23705, doi:10.1029/2005GL024550

Hayhoe, K., D. Cayan, C. B. Field, P. C. Frumhoff, E. P. Maurer, N. L. Miller, S. C. Moser, S. H. Schneider, K. N. Cahill, E. E. Cleland, L. Dale, R. Drapek, R. M. Hanemann, L. S. Kalkstein, J. Lenihan, C. K. Lunch, R. P. Neilson, S. C. Sheridan, and J. H. Verville. 2004. Emissions pathways, climate change, and impacts on California. Proceedings of the National Academy of Sciences 101:12422-12427.

Jackson, R. B., E. G. Jobbagy, R. Avissar, S. B. Roy, D. J. Barrett, C. W. Cook, K. A. Farley, D. C. le Maitre, B. A. McCarl, and B. C. Murray. 2005. Trading water for carbon with biological carbon sequestration. Science 310:1944-1947.

Jin, J., and N. L. Miller, 2008: Coupling an advanced land model into MM5 to improve regional snow simulation. Submitted to Journal of Geophysical Research (Submitted).

Jin, J., X. Gao, Z.-L. Yang, R. C. Bales, S. Sorooshian, R. E. Dickinson, S.-F. Sun, and G.-X. Wu, 1999: Comparative analyses of physically based snowmelt models for climate simulations. J. Climate, 12, 2643-2657.

Kuchler A.W., 1964. Potential Natural Vegetation of the Conterminous United States, Special Publication No. 36, American Geographical Society: New York.

Kuchler A.W., 1975. Potential Natural Vegetation of the Conterminous United States, 2nd Ed., American Geographical Society: New York. http://www.cgd.ucar.edu/vemap/kuchler2vveg.html (accessed Nov. & Dec. 2007) for amalgamation of Kuchler vegetation classes

Kueppers, L. M., M. A. Snyder, L. C. Sloan, E. S. Zavaleta, and B. Fulfrost. 2005. Modeled regional climate change and California endemic oak ranges. Proceedings of the National Academy of Sciences 102:16281-16286.

Lenihan, J. M., R. J. Drapek, D. Bachelet, and R. P. Neilson. 2003. Climate change effects on vegetation distribution, carbon stocks and fire regimes in California. Ecological Applications 13:1667-1681.

Lenihan, J., D. Bachelet, R. P. Neilson, and R. Drapek2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. Climatic Change 87 (Suppl 1): S215-S230.

Leung, L. R., Y. Qian, X. D. Bian, W. M. Washington, J. G. Han, and J. O. Roads. 2004. Mid-century ensemble regional climate change scenarios for the western United States. Climatic Change 62:75-113.

Luers, A. L., D. R. Cayan, G. Franco, M. Hanemann, and B. Croes. 2006. Our Changing Climate: Assessing the Risks to California, A Summary Report from the California Climate Change Center. CEC 500-2006-077, California Climate Change Center, Sacramento, CA.

Miller, N. L., and Coauthors, 2007: The California regional climate model intercomparison, California climate change conference, 10-14 Sept. 2007, Sacramento, CA.

Oleson, K.W., Y. Dai, G. Bonan, M. Bosilovich, R. Dickinson, P. Dirmeyer, F. Hoffman, P. Houser, S. Levis, G.-Y. Niu, P. Thornton, M. Vertenstein, Z.-L. Yang, and X. Zeng, 2004: Technical Description of the Community Land Model (CLM), NCAR/TN 461+STR, 174 p.

Ornduff R., Faber P.M., and Keeler-Wolf T., 2003. Introduction to California Plant Life, University of California Press: Berkeley, CA.

Schoenherr A.A., 1992. A Natural History of California, University of California Press: Berkeley, CA. accessed on-line (via a UC address) at http://www.netlibrary.com/summary.asp?id=4634 during Oct/Nov 2007.

Sellers, P. J., 1985: Canopy reflectance, photosynthesis and transpiration. Int. J. Remote Sensing, 6, 1335-1372.

Smirnova, T. G., J. M. Brown, S. G. Benjamin, and D. Kim, 2000: Parameterization of cold-season processes in the MAPS land-surface scheme. J. Geophys. Res., 105 (D3), 4077–4086.

Snyder, M. A., and L. C. Sloan. 2005. Transient future climate over the Western U.S. using a regional climate model. Earth Interactions 9:Paper 11.

Snyder, M. A., J. L. Bell, L. C. Sloan, P. B. Duffy, and B. Govindasamy. 2002. Climate responses to a doubling of atmospheric carbon dioxide for a climatically vulnerable region. Geophysical Research Letters 29:10.1029/2001GL014431.

Snyder, M. A., L. C. Sloan, N. S. Diffenbaugh, and J. L. Bell. 2003. Future climate change and upwelling in the California Current. Geophysical Research Letters 30:DOI:10.1029/2003GL017647.

Snyder, P. K., C. Delire, and J. A. Foley. 2004. Evaluating the influence of different vegetation biomes on the global climate. Climate Dynamics 23:279-302.

Torn, M., and J. Harte. 2006. Missing feedbacks, asymmetric uncertainties, and the underestimation of future warming. Geophysical Research Letters 33:doi:10.1029/2005GL025540, 022006.

Zeng, X., M. Shaikh, Y. Dai, R.E. Dickinson, and R. Myneni, 2002: Coupling of the Common Land Model to the NCAR Community Climate Model. J. Climate, 15, 1832–1854.

Appendix A – List of Acronyms

CLM3	Common Land Model, version 3
DVM	Dynamic vegetation model
FCAV	Future climate, afforested (and future native) vegetation
FCFV	Future climate, future native vegetation
FCHV	Future climate, historic native vegetation
GCM	Global climate model (or general circulation model)
GFDL	Geophysical Fluid Dynamics Laboratory
HadCM3	Hadley Center Coupled Model, version 3
HCHV	Historic climate, historic native vegetation
LAI	Leaf area index
LH	Latent heat
LWup	Longwave upward flux
m	meter
MC1	MAPSS-Century dynamic vegetation model
NCAR	National Center for Atmospheric Research
PCM	Parallel Climate Model
PFT	Plant functional type
RCM	Regional climate model
SH	Sensible heat
WRF	Weather Research and Forecasting model