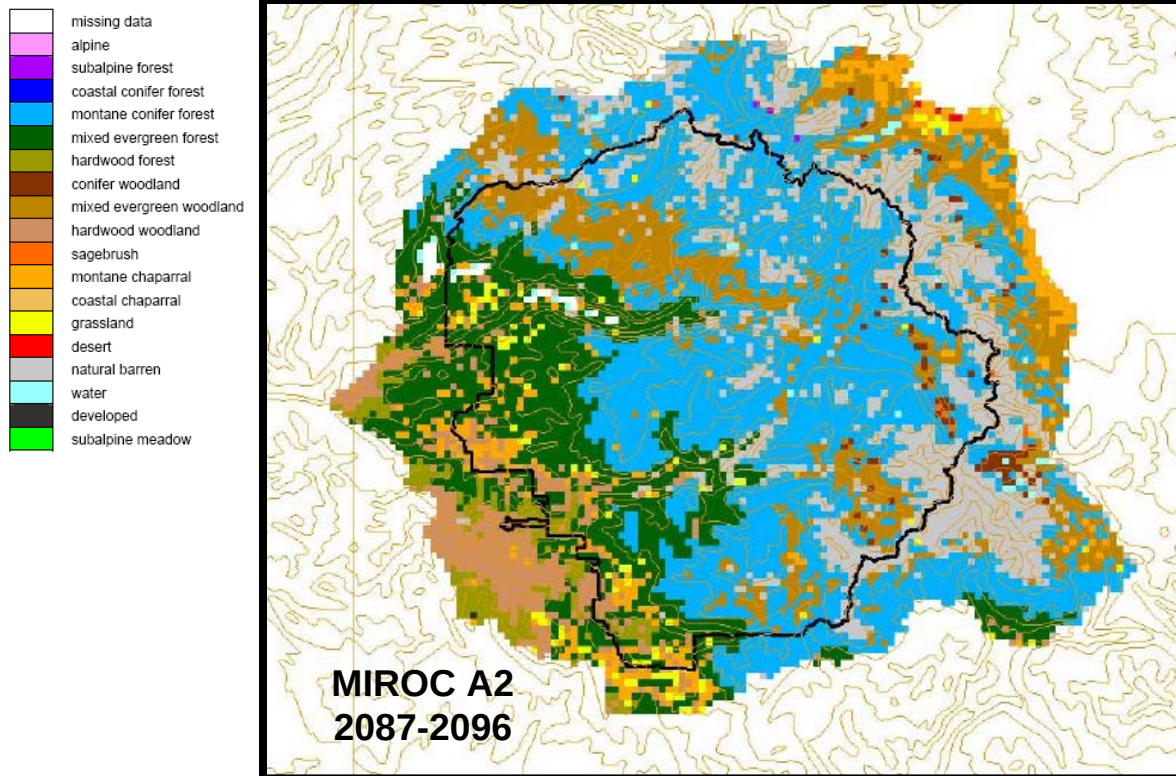


Projected Vegetation Changes Over the 21st Century in Yosemite National Park Under Three Climate Change and CO₂ Emission Scenarios



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Table of Contents

Abstract.....	iv
1. Introduction/Purpose.....	1
Changes over the last 100 years - Physical changes.....	1
Changes over the last 100 years - Ecological changes	2
Range shifts.....	3
Tree mortality.....	3
Invasive species, pests and pathogens	3
Fire	4
Projections for the next 100 years	4
Addressing the unknowns of climate change with models.....	5
2. Methods	6
MC1 dynamic vegetation model	6
Climate models	7
Climate data	7
Scenarios	8
Yosemite National Park Region Study Area	8
Physical Setting.....	8
Biological Setting.....	9
Observations: Vegetation, soil surveys, fire history, and fuels data	9
Fire index	11
3. Results.....	11
Temperature and Precipitation trends	11
Comparison of the simulated MC1 baseline vegetation map and the Yosemite 1997 vegetation survey.....	12
Past shifts in vegetation: Comparison of the 1930 and the 1997 Yosemite vegetation surveys	13
Future shifts in vegetation by scenario	14
CSIRO B1 Scenario	14
Hadley A1B Scenario	15
MIROC A2 Scenario.....	15
Shifts in vegetation summary.....	16
Carbon	16
Net Primary Productivity	16
Net Ecosystem Productivity.....	17
Net Biome Productivity	17

Summary of carbon dynamics	17
Fire	18
Fire emissions	18
Fire frequency and area.....	18
Fuel loads	19
Fire index	20
Uncertainty	20
Next Steps	21
4. Acknowledgements.....	22
5. References	22
6. Data sources and non-peer reviewed sources	26
7. Figures	28
Appendix 1.....	51

Abstract

Natural resource managers are faced with a daunting challenge, as parks and wilderness areas are now—and will continue to be—influenced by climate shifts. Management decisions are needed now to protect future resources and to plan for resource response to climate change – all without knowing what the future will bring.

Developing scenarios of potential future climates, and linking those with dynamic global vegetation models (DGVMs), provide projections of future vegetation changes across the landscape. These have proved useful to policy makers and resource agencies at the state and national scale. Only recently has it been possible to downscale the projections to regional scales as management tools for park and regional resource managers.

In this study, three future climate scenarios were selected for Yosemite National Park from a set developed by the Intergovernmental Panel on Climate Change, to span a broad range of scenarios from “small change in human behavior” (high CO₂ and hot, dry future) to “aggressive mitigation response” (moderate CO₂ and slightly warmer, slightly drier future). The DGVM MC1 model was used to predict vegetation shifts, carbon cycling, and fire dynamics in the Yosemite Park region through the end of this century.

There is no way to know how humans will behave over the next hundred years, nor is it possible to predict vegetation and fire dynamics with absolute accuracy. However, by focusing on similarities in the set of model projections, managers get powerful and robust results that point to likely future outcomes.

A summary of our projections for Yosemite National Park during the 21st century follow.

Under all scenarios:

Climate and Hydrology

- Temperatures in the Park increase, especially minimum temperature in winter
- Snowpack is reduced
- Snowmelt happens earlier

Carbon Cycle

- Yosemite ecosystems become net sources of CO₂ to the atmosphere at some point in the 21st century
- Declines in carbon pools occur under all scenarios but for different reasons
- Overall plant biomass declines, however belowground productivity tends to increase while aboveground productivity decreases

Fire

- Forest, woodland and shrubland fire area, and carbon emissions from wildland fires increase over the 21st century
- Fire drives major changes in montane conifer forests

Montane Chaparral and Hardwoods

- Lower elevation western Yosemite areas see incursions of hardwood woodlands and chaparral.
- Chaparral incursions into areas currently dominated by other vegetation types are facilitated by wildland fire.

Montane Ecosystems

- The montane conifer forests are the most robust of the forest ecosystems to increased temperature and drought, but they are also susceptible to wildland fires that, in this model, enable vegetation shifts.

Subalpine Ecosystems

- The subalpine conifer forests shift up-slope and decrease in total area, driven by warming temperatures.
- The subalpine forest zone disappears almost completely in 2 of the 3 scenarios.

Alpine Vegetation Communities

- Alpine vegetation communities are lost

Desert

- Desert vegetation, novel to the region, is projected to appear under all scenarios on the eastern side of the Sierra Nevada.

1. Introduction/Purpose

Climate change is causing profound shifts in the ecology of western ecosystems in North America. Northwestern North America has warmed by 1 °C to 2 °C since 1950, with the most pronounced warming in the winter and spring (Cayan et al. 2001). Along the Pacific coast, mountain snow is melting earlier, leaving diminished snowpack and lowered hydrologic reserves (Stewart et al. 2004, Mote et al. 2005). Sierra Nevada glaciers are retreating (Bassagie and Fountain 2006) and peak streamflows happen earlier (Stewart et al. 2004). Moreover, extreme precipitation events are increasing (Bell and Sloan 2006). The ecological consequences of these physical and hydrologic changes include earlier phenology (e.g. bud-break, migrations, nesting, hatching, Root et al. 2003); northward and upward shifts in elevation ranges in butterflies (Parmesan et al. 1999, Crozier 2003), migratory birds (Root et al. 2003), and rodents (Moritz et al. 2008); and climate-driven increases in fire frequency and burn area (Westerling et al. 2006, Stephens and Ruth 2005). California's climate over the next 100 years is projected to become hotter, and Sierra Nevada snowpack to shrink significantly, leaving Sierra Nevada ecosystems parched (Cayan et al. 2006). Because of earlier snowmelt, the summer dry season is also predicted to lengthen, which would lead to significant changes in vegetation distribution. As vegetation shifts to areas of physiological "comfort", so might the animals that depend on those plants. Drier summers will likely lead to further increases in fire frequency and greater area burned, further affecting the spatial distribution of both local fauna and flora.

Robust predictions of how changing climate will influence vegetation distributions and fire across the landscape will provide critical information for sound management plans and actions. Knowing how vegetation will shift is key to understanding how wildlife species are likely to shift their distribution. Predicting how future climate will affect wildland fire occurrence and extent across the landscape is critical to planning fire management strategies today. Feedbacks between vegetation and fire control the species assemblages that characterize western ecosystems. Vegetation and wildland fire projections are being developed in many areas of the world using sophisticated climate and dynamic vegetation simulation models. The goal of this project was to apply a widely-used, state-of-the-art dynamic global vegetation model (DGVM) at Yosemite National Park to generate projections of future potential vegetation distribution and dynamics, fire occurrence and impacts, and carbon cycling gains and losses to help resource managers prepare for the future. In particular, this modeling project should help Yosemite resource managers answer the following questions:

- How might Yosemite's vegetation change in the future?
- What vegetation types are most at risk of declining or even disappearing?
- How might disturbance regimes and ecosystem processes be affected by climate change

Changes over the last 100 years - Physical changes

Physical changes are already occurring in the Sierra Nevada and in Yosemite National Park due to changes in climate. Spring temperatures in western states have warmed by 1 °C to 2 °C since 1950 (Cayan et al. 2001). This change is greater than the

global annual average of 0.8 °C. Spatially heterogeneous warming is predicted by climate models. Some areas of the earth, such as western states, are predicted to warm more than others. The Sierra Nevada has already warmed 0.5 °C to 1.5 °C in the last 50 years (Mote et al 2005) following a generally cool mid-century period (Taylor and Hatton, 2003, Dettinger and Cayan 1995) with Yosemite experiencing the higher end of that warming range (Mote et al. 2005). Recent research suggests that changes in the relative frequency of different patterns of upper air flow could result in less warming or even cooling on the east slope of the Sierra Nevada, at the same time as the region west of the Sierra Nevada crest continues to warm (Lundquist and Cayan 2007).

As a consequence of higher temperatures, Sierra Nevada snowpack is melting earlier, streams are experiencing peak flows earlier, and water is draining from montane ecosystems on average earlier (Stewart et al. 2004; Mote et al. 2005), although substantial basin to basin variability has been observed (Lundquist and Flint 2006). This general trend has resulted in an increase in the length of the summer drought period, and ecosystems are now drier by the end of the dry season (September/October). Snowpack throughout western U.S. mountains has greatly diminished over the last 50 years (Mote et al. 2005). In the Sierra Nevada, however, increased precipitation over the same time period at high elevation has somewhat mitigated the effects of increased melting, but mid-elevations have experienced the greatest extent of spring snowmelt.

The Sierra Nevada contains approximately 497 alpine glaciers and perennial ice features (Raub 1980). Like glaciers around the world, Sierra Nevada glaciers have retreated over the last 100 years. Repeat photography techniques have been used to document the retreat of 10 Sierra Nevada glaciers (Basagic and Fountain 2006). For example, the Lyell glacier in Yosemite has retreated by 50% since 1883.

Another predicted consequence of global climate change is an increase in the frequency and severity of extreme weather events. Extreme precipitation events have already increased in western states (Bell and Sloan 2006), as they have around the world. While individual events, like the recent floods in Yosemite Valley in winter 1996/7 or in spring 2005, cannot be specifically attributed to climate change, they are consistent with what would be expected under climate change scenarios with warmer winter and spring temperatures and rain-on-snow events melting snow rapidly. Longer periods of summer drought have also been projected as a possible consequence of climate change for California.

Changes over the last 100 years - Ecological changes

In addition to the physical changes that have been documented, related biological and ecological changes have begun to be observed. It is difficult to tease out a climate signature from the web of interactions that make up the ecology of an ecosystem. There are many interdependencies between organisms, and between organisms and their environment, so that cause and effect are generally difficult to attribute at the local scale. However, researchers have used meta-analysis to identify a climate fingerprint on phenological changes worldwide, including generally earlier timing of life-cycle events in trees and other vegetation, insects, fish, mammals, and birds linked with temperature (Root et al. 2003).

Range shifts

World-wide, significant changes in species ranges have been documented and linked with temperature shifts. As expected, these range shifts have been pole-ward and upward in elevation following either temperature shifts or resulting vegetation shifts. In the western United States, notable range shifts have been observed in butterflies, migratory birds and rodents. Of the 58 butterfly species studied, two-thirds have shifted their ranges northward. The sagem skipper butterfly (*Atalopedes campestris*) has expanded its range from California to Washington State (420 miles) in just 35 years (Crozier 2003). During the single year 1998—the warmest on record before 2003—the butterfly range expanded 75 miles northward.

Range shifts have been observed in and around Yosemite National Park. A recent research effort took advantage of the 1914 Grinnell survey, which documented the presence of species along a transect through Yosemite nearly 100 years ago (Moritz et al. 2008). Resurveying Grinnell's sites over the last 3 years, researchers have found dramatic changes in species ranges over the last century. The piñon mouse (*Peromyscus truei*) was found 3,200 vertical feet higher and 8 miles from the nearest Grinnell sighting. Four other small mammals have expanded their ranges in the park, increasing their upper limits by an average of 2000 vertical feet. In contrast, high elevation species have experienced an apparent contraction of their ranges. The alpine chipmunk (*Tamias alpinus*), two high-elevation small mammals (*Spermophilus beldingi*, *Sorex palustris*) and the pika (*Ochotona princeps*) have retracted the lower edge of their ranges by an average of 1,700 feet. At least two species of small mammals, a chipmunk (*T. senex*) and a woodrat (*Neotoma cinerea*), have dramatically shrunk the overall size of their ranges, and are now extremely rare in the park (Moritz et al. 2008). Moreover, seventeen bird species were recorded in high elevation Lyell Canyon in the recent re-survey which were not mentioned by the Grinnell team, many of them riparian and wetland species more common at lower elevations. The blue-winged teal (*Anas discors*) and the mallard (*A. platyrhynchos*) were found breeding for the first time in the canyon's high-elevation meadows (Rush 2005).

Tree mortality

Tree demographic data for coniferous forest types within Yosemite, Sequoia, and Kings Canyon National parks in the Sierra Nevada indicate that tree mortality has increased significantly over a 22-year period between 1983-2004 (van Mantgem & Stephenson 2007). The rate of mortality of pines (*Pinus spp*) and firs (*Abies spp*) within old growth stands across an elevational gradient doubled over the 22 -year monitoring period. Mortality primarily occurred in the smaller size classes. Over the period of study, precipitation was unchanged but temperatures gradually increased, raising the overall drought index. Tree mortality rates were best predicted by soil water deficits. An increasing trend in the mortality rate of young pines and firs may signal climate change effects. Although the proximate cause for the increased mortality has been attributed to increased stress, pathogens, and pests (due to a decrease in soil moisture), the ultimate cause is thought to be the changing climate.

Invasive species, pests and pathogens

Invasive species, pest and pathogen ranges have responded to shifts in climate. In

British Columbia, the mountain pine beetle (*Dendroctonus ponderosae*) range has expanded dramatically due to a warmer climate that released it from temperature limitation. The beetle is predicted to decimate 80% of the pine population by 2013, with enormous ecological and economic consequences (Kurz et al. 2008).

Sleeper invasives are exotic species that are currently resource limited and could be released from limitation by climate change. Research indicates that many invasive weed species might be better able to take advantage of the fertilization effect of increased CO₂ concentrations than native species (eg., Ziska and George 2004). Species from lower elevations and lower latitudes may migrate up and into the park. Pest populations may explode locally as they have elsewhere (Kurz et al. 2008).

Fire

Fire response to climate change is a complex issue, made more complex by suppression policies of the past 100 years. Fire regimes are known from paleoecological evidence to vary through time in response to changing climate. Hotter, drier conditions tend to increase fire frequency, which generally shifts vegetation toward more fire-tolerant species (Clark 1990, Swetnam 1993, Veblen et al. 1999). However, increased fuel loads and altered species composition on fire-suppressed lands have left these areas more susceptible to fire, independently of climate.

The area burned by fire annually in western states has increased despite increased infrastructure and resources to extinguish fire (Stephens and Ruth, 2005; Westerling et al. 2006). This increase in fire frequency and burn area in the West has been attributed primarily to climate (Westerling et al. 2006).

Projections for the next 100 years

Recent publications have provided insights into direct and indirect large-scale climate impacts on California (eg., Hayhoe et al, 2004, CalEPA 2006, Cayan et al. 2006) using future climate change scenarios from the Intergovernmental Panel on Climate Change (IPCC) most recent projections (IPCC 2007). The set of scenarios used for California span the range from “no change in human behavior” (high CO₂ and hot, dry future – hotter than the one chosen for this report) to “aggressive mitigation response” (moderate CO₂ and slightly warmer, slightly drier future – same as the one chosen for this report). In general, California is projected to become warmer – the increase in temperature is dependent on potential future scenarios of CO₂ emissions. The highest emission scenario may lead to temperatures as much as 10.5 °F (5.8 °C) warmer than today, while the medium emission scenario leads to an 8 °F (4.4 °C) increase. The effect of climate on precipitation is uncertain enough that it is currently difficult to project whether California will become wetter or drier. But even under wetter conditions, the increase in temperature will likely enhance evaporation and transpiration fluxes and cause drought stress. Warmer temperatures will also likely bring more winter precipitation in the form of rain rather than snow. Snow is California’s summer water source, so summer water will become increasingly scarcer, for natural ecosystems as well as for humans. These changes will have severe impacts on the Sierra Nevada and California in terms of water storage, water demand, sustainability of agriculture, and resilience of native ecosystems (Cayan et al. 2006, Table 1).

The climate effects projected for California that will likely also impact the Park

include an inevitable loss of Sierra Nevada snowpack, regardless of scenario. Up to 80% of the average winter snowpack could be lost by the end of the century under even the medium-range emission scenarios. The length of the fire season could increase, even under moderate scenarios. Finally, days conducive to ground-level ozone formation might increase by 75% to 85%, with direct effects on vegetation, animals and visitors in the park.

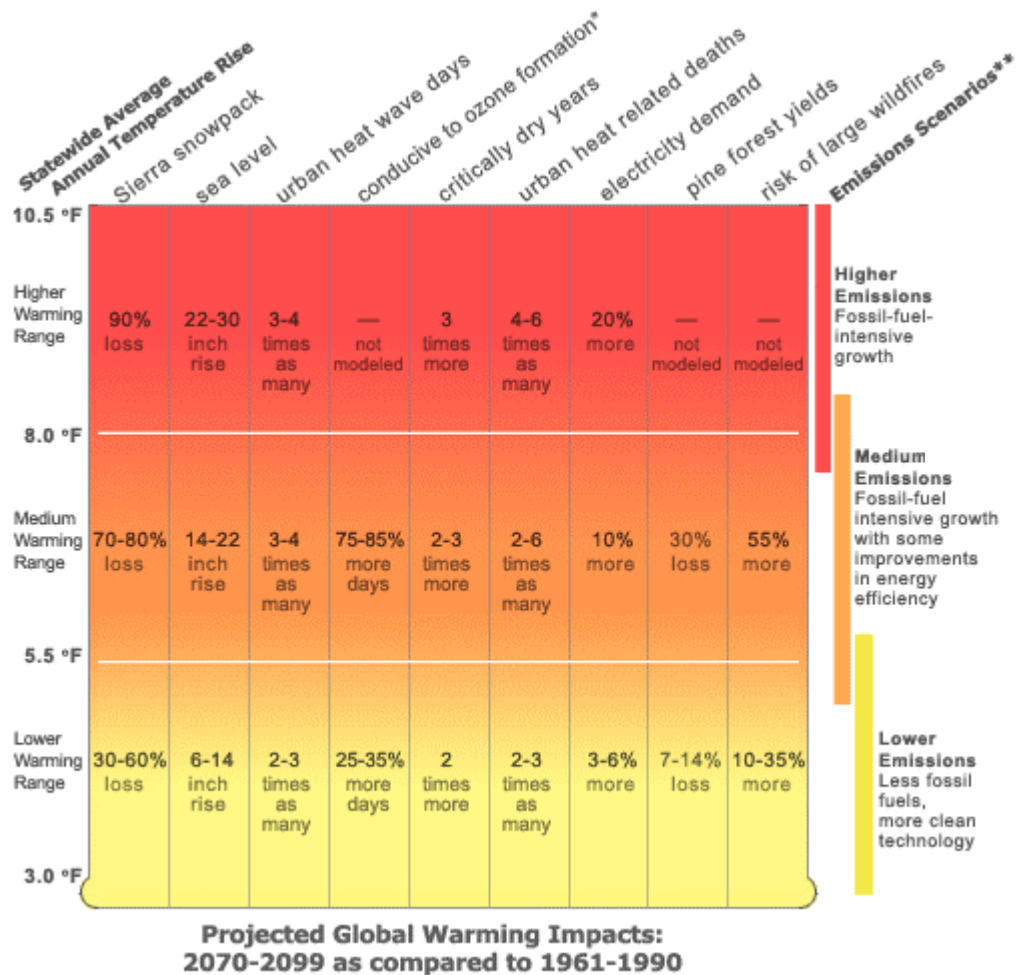


Table 1. California-wide predictions based on three IPCC scenarios (modified from Cayan et al. 2006 by UCS 2006; used with permission of the authors).

Addressing the unknowns of climate change with models

Understanding possible outcomes from climate change impacts on economic and ecological resources is essential for policy makers, and such assessments have been undertaken at many scales and in many sectors. Climate models, vegetation models, and projection techniques are being developed to provide plausible scenarios for future vegetation shifts to resource managers. Trends in vegetation dynamics, in response to climate change, have been projected over many parts of the world using dynamic

vegetation simulation models and IPCC climate projections. MC1, the model described in this report, has been used to generate dynamic simulations for the globe (Gonzalez et al. 2005), North America (Price et al. 2004), the United States (Bachelet et al. 2008) and California (Lenihan et al. 2003, Lenihan et al. 2008), generating potential vegetation maps for various climate scenarios. The model projects vegetation shifts, simulates potential losses and gains of certain vegetation types, documents changes in ecosystem processes, and in general has been useful in understanding possible regional consequences of greenhouse gas emission reduction scenarios. Because of the broad scale and coarse resolution of the output (10 km), model results have been too general for local applications, like those needed for national parks.

Downscaling projections to provide information at finer resolution needed for resource management has only become possible recently as finer resolution climate data have become available. This study takes on the downscaling challenge and applies a widely-used, state-of-the-art dynamic vegetation model – MC1 – to the Yosemite Park region to investigate the sensitivity of natural ecosystems under 3 climate scenarios and to provide park resource managers with a tool to better prepare for vegetation shifts.

With results from this study, resource managers can:

- Plan actions to protect natural vegetation resources in anticipation of projected shifts and changes in community distributions, composition, and function
- Identify potential fire risk, frequency, intensity, emissions and the spatial distribution of fire across the landscape
- Understand spatial linkages with surrounding lands (USFS, BLM, cities, counties)
- Anticipate future needs in park infrastructure, facilities, and planning
- Prepare for changes in visitor experience and expectations
- Use in public outreach materials to educate the public

It is a challenge to manage national parks in the face of a changing climate. Yosemite is one of the most prominent national parks. Visitorship peaks at more than 573,000 visitors a month in the summer (www.nature.nps.gov/stats/park.cfm). Yosemite harbors a large diversity of landscapes and natural ecosystems that must be managed in the context of a changing climate. It also attracts excellent ecological and hydrological scientific scrutiny that can link to, and build on, the results of studies like this one to provide further resources for park managers.

2. Methods

MC1 dynamic vegetation model

MC1 (Daly et al. 2000, Bachelet et al. 2001b) is a dynamic vegetation model that simulates lifeform mixtures and resulting potential vegetation types. It was originally developed as a hybrid of the MAPSS biogeography model (Neilson 1995) and the Century biogeochemistry model (Parton et al. 1994). It also includes a dynamic fire model (Lenihan et al. 1998). MC1 simulates fluxes of carbon, nitrogen, water, and fire (Figure 1). MC1 is routinely implemented (Bachelet et al. 2000, 2001a; Daly et al. 2000; Lenihan et al. 2008) on spatial data grids of varying resolution (i.e., grid cell sizes

ranging from 1 to 2,500 km²).

The biogeography module simulates several lifeforms: evergreen needleleaf and broadleaf trees, deciduous needleleaf and broadleaf trees, and C3 and C4 grasses. The biogeochemistry module simulates plant productivity, organic matter decomposition, and water and nutrient cycling. The fire module simulates the occurrence, behavior, and effects of fire and consists of several mechanistic fire behavior and effect functions (Rothermel 1972, Peterson and Ryan 1986, van Wagner 1993; Keane et al. 1997, Lenihan et al. 2006) embedded in a structure that provides two-way interactions with the biogeography and biogeochemistry modules.

Climate models

Three general circulation models (GCMs) were chosen to bracket the range of scenarios available for the western USA: the CSIRO-MK3.0 model (Gordon et al. 2002, Dix et al. 2009) from Australia, the Hadley CM3 model from the UK (Gordon et al. 2000, Pope et al. 2000) and the MIROC 3.2 medium resolution model from Japan (Center for Climate Systems Research 2004) (Table 2).

Table 2. Description of the three general circulation models used in this study.

	Cell size (°Lat)	Cell size (°Long)	Vertical layers	Reference
CSIRO	0.8	1.9	31	Gordon et al. 2002
Hadley	1.25	1.25	20	Gordon et al. 2000
MIROC	0.5-1.4	1.4	43	Center for Climate Systems Research 2004

Climate data

Monthly historical climate data were generated by Chris Daly and the PRISM Group at Oregon State University on a 30 arc-seconds of latitude and longitude (~800 m) grid from station data using the PRISM climate interpolation technique (Daly 2006). The data span the years 1895 through 2006, and include maximum, minimum and dewpoint mean monthly temperature, and mean monthly precipitation.

A one-year monthly climatology, calculated as the average conditions between 1971 and 2000, was used to initialize potential vegetation by running MC1 until the recalcitrant soil carbon pool reached quasi-equilibrium values while prescribing fire events. An annual time series was generated by detrending the 112-year PRISM historical climate data set to match the observed climate means of the period 1895-1909. MC1 was then run using this spinup dataset for 1,008 years using dynamic wildland fire simulations until net ecosystem production settled near zero. PRISM historical climate data set was then used to simulate observed historical conditions between 1895 and 2006.

The process of preparing the future (2007-2099) climate data had several steps. The first step was to calculate a mean monthly climatology for the 30-year period 1971-2000 using PRISM historical climate data and for the climate data from MIROC, Hadley, and CSIRO climate models. The second step was to calculate the monthly anomalies of the three future scenarios from the 1971-2000 mean climatologies. Difference anomalies

were calculated for temperature data and ratio anomalies were calculated for precipitation. The final step was to apply the monthly anomalies for the three future climates to the PRISM historical mean monthly climatology.

Scenarios

We used 3 emission scenarios to bracket socio-economic options following the IPCC 2007 range (Figure 2).

- The A2 high emission scenario projects continuous population growth with slower economic growth and technological change than in the other two scenarios.
- The A1B medium emission scenario describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies, with a balance of dependence on fossil and non-fossil energy sources.
- The B1 lower emission scenario describes a world with a population that peaks in mid-century and declines thereafter, as in the A1B scenario, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies.

The scenarios chosen from the 9 available in this study are outlined in red in Figures 3a,b. The diagonal represents the combination of 1) hottest, driest, highest greenhouse gas (GHG) scenario (A2/MIROC 3.2), 2) a moderate rise in temperature, a moderate decrease in precipitation and moderate level of GHG emissions (A1B/Hadley CM3), and 3) the coolest, lowest GHG scenario (B1/CSIRO MK3).

Yosemite National Park Region Study Area

Physical Setting

Yosemite National Park covers 747,958 acres (302,688 ha) of the western slope of the central Sierra Nevada and spans elevations from 500 meters on the western side up to 3,997 meters at the Sierra crest along its eastern border.

The study area extends beyond the park boundary on all sides and covers an area of 1,388,025 acres (561,714 ha). This area was selected since it is the extent of the 1997 vegetation survey and digital map data, representing the most current vegetation base map for the park and adjacent lands. Elevations within the study area range from 394 meters on the western side to 4,006 meters along the crest.

The large majority of Yosemite's geologic foundation is plutonic igneous rocks, dominated by granites (Huber 1987, Bateman 1992). The surface of the park and most adjacent lands have been heavily modified by glacial forces that have formed the deep carved valleys, peaks and exposed granitic domes found today. Due to the recent glacial history and granitic bedrock, soils that formed are generally shallow, poorly developed,

rocky, and low in fertility. Soils that escaped glaciation along the park's western margin are thicker and better developed. In the large canyons that bisect the park, glacial tills have accumulated to form very deep soils.

Yosemite lies within the Sierra Nevada ecosystem of California. The lower and middle elevations experience a modified Mediterranean climate characterized by cool to cold and wet winters and dry, hot summers. Higher elevations experience an alpine type climate that is characterized by a short, warm growing season and a long, cold winter where average daily temperatures are below 0 °C in the coldest month. The park currently receives its precipitation primarily as rain at elevations below approximately 2000 meters and primarily as snow at elevations above this (Stephenson 1988). The park receives between 0.5 m and 2 m of rain annually, approximately 70% of this falling between December and April.

Biological Setting

The vegetation of the study area can be categorized broadly into chaparral, foothill woodland, lower montane broadleaf forest, lower montane needleleaf forest, upper montane needleleaf forest, subalpine needleleaf forest, alpine dwarf shrub, and meadow. Since 80% of the study area lies above 1,800 m (~6,000 ft), the park is dominated by coniferous (needleleaf) forests and woodlands which cover approximately 68% of the study area. There are small but significant amounts of lower montane broadleaf forests and woodlands (38,613 ha or 7% of the study area) and chaparral shrublands (53,763 ha or 9.5% of the study area). Unvegetated to sparsely vegetated areas, including granitic domes and outcrops, and talus slopes, cover 87,166 ha or 15.5% of the study area.

Observations: Vegetation, soil surveys, fire history, and fuels data

Historical vegetation data were derived from Yosemite's 1997 vegetation map (Aerial Information Systems 1997). These data were derived from a coordinated process of photo-interpretation, field reconnaissance, plot sampling, verification, and accuracy assessment. Color infrared aerial photography (1:15,860) taken in August of 1997 was used as a basis to map the vegetation within the park and surrounding lands (Aerial Information Systems, 1997). In 1998 and 1999, 604 vegetation plots were surveyed within the vegetation mapping study area. A plant community floristic classification system was developed by running a cluster analysis on the 604 plots surveyed in 1998-99, 362 plots surveyed between 1989 and 1993, and 774 sites surveyed between 1935 and 1937 (NatureServe 2007). A list of vegetation types was developed and crosswalked to the floristic classification based on cluster analysis. A class was assigned to each polygon mapped during the photointerpretation. Using a minimum unit of 0.5 hectares, vegetation polygons were assigned a vegetation association, superassociation, alliance, or superalliance, depending upon the degree of confidence. If identified vegetation polygons did not closely match a previously described association or alliance, they were assigned a mapping classification. Finally, accuracy assessment field data were collected and analyzed and floristic classes aggregated as necessary to improve accuracy. After several rounds of quality assessment, a set of 129 distinct vegetation types was chosen. These 129 types were aggregated into 13 coarser categories, for the purpose of comparisons with MC1 output. The crosswalk from Park vegetation map classifications to MC1 classifications is shown in Table 3 and Appendix I. Meadows were split into three

groups. Meadows below 1,675 m (5,500 ft.) were assigned to the grassland vegetation type, meadows between 1,675 m and 3,050 m (5,500 ft. and 10,000 ft.) were assigned to the meadow type, while meadows above 3,050 m were assigned to the alpine dwarf shrub type.

Table 3. MC1 simulated vegetation types and Yosemite 1997 Survey representative species assemblages. See also Appendix I for more details.

MC1 vegetation class	Yosemite examples and species
Alpine dwarf shrub	Krummholz; alpine meadows
Subalpine forest	Sierra lodgepole pine forest; lodgepole, mountain hemlock forest; Sierra lodgepole, whitebark pine forest; Sierra lodgepole pine, quaking aspen, Jeffrey pine forest
Montane Conifer forest	Red fir forest; red fir, sugar pine, western white pine forest; Ponderosa pine, incense cedar forest
Mixed Evergreen forest	Ponderosa pine, California black oak, Incense cedar forest; Douglas-fir, ponderosa pine forest; white fir, Douglas-fir forest; canyon live oak, ponderosa pine forest
Hardwood forest	Canyon live oak forest; black oak forest; interior live oak forest
Conifer woodland	Ponderosa pine woodland; Jeffrey pine woodland
Mixed Evergreen woodland	Ponderosa pine, black oak woodland; foothill pine, interior live oak woodland
Hardwood woodland	Blue oak woodland; black oak woodland; Interior live oak, canyon live oak woodland
Sagebrush	Sagebrush, bitterbrush
Montane Chaparral	Chamise, <i>Ceanothus</i> , <i>Manzanita</i>
Grassland	Low elevation meadows; California annual grassland
Natural Barren	Rock domes, talus slopes
Meadow	Mid-elevation meadows

Soil data for the park and surrounding lands were derived from a Soils Conservation Service soils data set commonly used by the MAPSS team (USFS Pacific Northwest Research Station and Oregon State University). This soil dataset is problematic for our Yosemite study, because it does not include the large areas of bare rock in the high Sierra

Nevada. To get around that deficiency, we used a mask of barren cells derived from the 1997 Vegetation Survey. We made an effort to format a more detailed soils map using the Soil Survey Geographic database (SSURGO), but were unable to do so within the time and resource constraints of this project. This more recent soil map is based upon data from 453 soil pits collected in 2004 and 2005, and mapped using a 40 hectare minimum mapping unit (USDA NRCS, 2006).

We had planned to use the available fire information to calibrate our model, but again time and resource constraints prevented us to use the data for the report. Further work (Dave Conklin, Pers. Comm.) will include detailed comparisons of observations and simulations at Yosemite.

Fire history for the study area exists from detailed fire history information maintained by Yosemite and the California Dept. of Forestry and Fire Protection (CAL FIRE) for national forest lands outside the park, and will be compared to MC1 output in follow-up research from this study. Beginning in approximately 1908 on Forest Service lands, and in 1930 within Yosemite, fire perimeters were mapped, initially by hand, then later using GPS technology. All wildland fires and prescribed fires have been mapped and maintained in databases for California national forests (CAL FIRE 2007) and for Yosemite National Park (YNP 2007). Aggregate data for all years were digitized and translated into vector and raster datasets representing the fire history for every point within and outside the park.

A set of fuelbed inputs (fuel models) was developed by Scott and Burgan (2005) for use in the Rothermel (1972) surface fire spread model. These 40 different fuel models were then crosswalked to the vegetation types of the park's 1997 digital vegetation data. There are 24 fuel types within the study area.

Vegetation, soils, and fire history data in vector format were converted to raster datasets at the 0.5 minute (~800 m) raster grid scale to compare them with MC1 results using ArcGIS 9.2 (ESRI). Each grid cell was assigned the vegetation type that was present within the cell in the greatest amount. The same dominance rules were used to assign soil type, fire history, and fuels to each grid cell.

Fire index

A "fire index" was calculated to provide information on fire risk through the end of the century for resource managers. Areas were identified where fire impacts are most likely to be large, areas where resource managers might choose to focus treatment or further study. A fire index for each cell was calculated as the ratio of biomass consumed by fire to net primary production (NPP), for the 30 year interval 1971-2000 and for the 29 year intervals 2071-2099 for each of the 3 future scenarios, by post-processing MC1's output data for the cell's cumulative net primary productivity and the cumulative amount of biomass carbon consumed by fire during the particular interval.

3. Results

Temperature and Precipitation trends

Under all scenarios, the Yosemite study area is predicted to get warmer over the next 100 years (Figure 4 and Table 4). The trend in projected mean annual temperature is more pronounced than the trend in precipitation (Figure 4). However, for the last 3

decades of the 21st century, under all future scenarios, the region becomes drier and warmer than under historical conditions (Table 4).

Warmer spring temperatures has caused earlier snowmelt over the last 50 years (Mote et al. 2005, Stewart et al. 2004), and will continue to do so under all scenarios (Figure 5a). Spring snowmelt, as measured by the April 1st snow-water-equivalent (SWE) shows substantial declines in the last thirty years of the A2, A1B, and B1 scenarios respectively (Figure 5a and Table 4).

Table 4. Change in climate simulated under 3 CO₂ emission scenarios for Yosemite National Park, averaged over the 2069-2099 simulation period. Historical is averaged over the 1969-1999 period.

	A2	A1B	B1
Change in Temperature (historical: 5.8 °C)	+5.2	+4.1	+1.8
Change in Precipitation (historical: 98 mm)	-22 (-22.6%)	-13 (-12.8%)	-3 (-3%)
Spring snowmelt, ie. April 1 st snow water equivalent (historical: 678 mm)	213 (-69%)	362 (-47%)	457 (-33%)

For each pixel, MC1 identifies the first month of the year in which there is no snow on the ground. Those values were averaged across all the cells to calculate an average first snowfree month for our area of study, defined as the first calendar month in which the average snowpack = 0. The first snowfree month in Yosemite is currently, on average, June. Increasing temperatures in Yosemite will push the first snowfree period up to late February under A2, late March under A1B, and late April under B1 (Figure 5b).

The combination of warmer temperatures and earlier snowmelt, has profound consequences for water availability during plant growth periods. In the Sierra Nevada, much vegetation growth occurs in the spring and early summer months. Earlier snowmelt will leave the spring drier and summers profoundly dry. While some of the vegetation is adapted to summer drought and compensates by changing its physiology to maximize CO₂ uptake despite low water availability (Panek and Goldstein 2001), drier conditions may leave forests vulnerable to fire, as shown later in this report.

Comparison of the simulated MC1 baseline vegetation map and the Yosemite 1997 vegetation survey

The simulated modal vegetation distribution from the 1986-1997 period generally agrees with the Yosemite 1997 vegetation survey for areas within the Park boundary (Figures 6 and 7). The model simulates the broad extent of montane conifer forests in the western region although diversity around key features is lost, such as the mixed evergreen woodland and forest in the Tuolumne River canyon below and above Hetch Hetchy Reservoir and within and adjacent to Yosemite Valley. The subalpine forest extent is also simulated fairly well within the Park boundary, however the alpine type is overestimated. MC1 misses most of the details of the lower Tuolumne River canyon (and Hetch-Hetchy area) and the lower Merced River canyon (including Yosemite Valley), and therefore overpredicts montane conifer forest and subalpine forest (Figure 7). This may be because these two canyons have been dramatically altered by humans within the last 100 years, and MC1 predicts potential, not actual, vegetation. Moreover,

the model does not include rivers or any riparian processes that influence local ecological processes. For areas outside the Park boundary, MC1 did not capture some key vegetation features, such as the chaparral areas in the northeastern portion of the study area. In the western region, MC1 underpredicted the expanse of mixed evergreen forest and missed some detail in distribution of hardwood woodland, hardwood forest and montane chaparral (Figure 6b, 6c, 7). For any given pixel, the actual vegetation may differ from the potential vegetation due to land use and disturbance history or the inability of the model to capture microclimate complexity. Complete agreement between MC1's vegetation classes and the survey data is not expected. The fact that MC1 does not capture strong riparian influences on vegetation may become increasingly limiting when the model is used at increasingly higher resolution.

Past shifts in vegetation: Comparison of the 1930 and the 1997 Yosemite vegetation surveys

While not part of the original proposed scope of work, documenting the observed change in vegetation cover between the 1930s and the 1990s creates another test for the model that can allow partial recalibration if necessary. This supplementary work will eventually become part of Dave Conklin's Ph.D. thesis. In addition to the Yosemite 1997 vegetation survey map, there is also a set of vegetation maps produced in the 1930s by the Wieslander Vegetation Type Mapping Project (<http://vtm.berkeley.edu/>). The Wieslander maps for Yosemite and some other parts of California have now been converted to digital form at U.C. Davis (Thorne et al. 2008). With the assistance of the U.C. Davis group, we converted the Wieslander vegetation types, numbering in the hundreds, into the much more aggregated vegetation types used by the model (Figure 6a). The resulting map covers all of the area within the Park boundaries but omits the southeastern part of the study area outside the Park, which was not surveyed in the Wieslander project. Comparing the Wieslander map with the Yosemite 1997 survey map, we found a 38% difference in vegetation type over the entire study area. Some of these differences arise from imprecision in the methods we used to put the original Wieslander map and the original 1997 survey map into a grid format. Our grid includes 8,000 cells, while the Wieslander map includes about 11,000 and the 1997 survey includes 84,000 irregular polygons respectively. Moreover, different vegetation classification schemes were used in the 1930's (hundreds of classes) compared to the 1997 survey (129 classes). The processes of spatial resampling and vegetation class aggregation generate mis-registration of the edges of adjacent vegetation patches. This noise can show up as shifts in both directions between vegetation classes. To render the comparison between the two maps more tractable, we restricted our quantitative analysis to the area within the Park boundaries (4446 grid cells), and we analyzed only the percentage of switches for which there were no offsetting switches in the opposite direction, and only those remaining switches representing at least 0.5% of the Park area. This approach reduced the differences from 38% of the total study area to 23% of the area within the Park boundary. For some of these remaining differences, we compared maps of California Wildlife Habitat Relationship classes (CWHR, Mayer and Laudenslayer 1988) derived from the original Wieslander and 1997 survey maps. There are 37 CWHR classes relevant to our study area, so the CWHR classification scheme is intermediate in aggregation between the original mapped vegetation classes and the MC1

classes.

Of the remaining 23% difference, there is a net of 10% of the Park area in subalpine forest class on the 1930s map but in the montane conifer forest class on the 1997 map (11.1% switches from subalpine forest to montane conifer forest, and only 0.8% switches from montane conifer forest to subalpine forest). Virtually all (10% of the Park area) represents a switch from the CWHR lodgepole pine (LPN) class to the CWHR red fir (RFR) class. This difference is challenging to interpret, because the two species appear together, but with different relative dominance, in multiple classes in both the 1930s data and the 1997 survey. Nevertheless, the data is consistent with an interpretation that the area of montane conifer forest where red fir is dominant has increased, largely at the expense of subalpine conifer forest where lodgepole pine is dominant. An alternate hypothesis, that the difference arises from methodological differences between the 1930s survey and the 1997 survey, is also plausible.

The final 13% difference consists of many different switches, but only three have net percentages larger than one percent. One is a switch from conifer woodland into montane conifer forest (net 2.9%), which could represent densification or merely differing standards for discriminating woodland from forest. The second is a switch from mixed forest to montane conifer forest (net 2.3%), which is puzzling. The third, a switch from conifer woodland to subalpine forest (net 1.2%), could represent densification at higher elevations, consistent with warming minimum temperatures and increased precipitation. Sorting out the 20th century changes comprehensively is outside the scope of the present study, but is the subject of ongoing work by one of the authors. Observed differences, especially those less than 10%, should be interpreted with caution.

Future shifts in vegetation by scenario

CSIRO B1 Scenario

In the least-warm and highest-precipitation future CO₂ emission scenario (B1), the area inside the park boundary sees a shift of montane conifer forests upwards in elevation into the subalpine forest realm and a shrinking of the subalpine forest type (Figure 9a). There is also an almost complete loss of the alpine dwarf shrub vegetation type. Mixed evergreen woodland and chaparral expand at mid-elevation, interspersed within a largely-intact montane conifer forest. The lower elevations outside the park sustain the greatest changes. Incursions of hardwoods and chaparral occur at southwestern lower elevations and mixed evergreen forest spread northward into what was previously montane conifer forest. Moreover, sagebrush expand into the eastern low-elevation montane conifer forest. Note that simulated vegetation maps show loss of vegetation type, but should be interpreted as loss of area optimal for that particular vegetation type. The trees themselves may persist significantly longer than optimal conditions for their growth..

Compared with the simulated historical vegetation distribution, 40% of the cells change vegetation class. The change in vegetation from subalpine forest to montane conifer forest (12% of study area) and the shift from montane conifer to mixed evergreen forest (7%) are the direct results of warming, based on MC1 model biogeography rules (Figure 9b). In general, the changes in the B1 scenario, the coolest, moistest of the scenarios, are governed by changes in temperature.

Hadley A1B Scenario

The A1B scenario, the moderate warming and drier scenario, shows large changes at higher elevations (Figure 10a). The alpine dwarf shrub vegetation type is completely lost and subalpine forest vegetation types are nearly lost (except for a few relics to the north) as montane conifer forest spreads upward and over the crest of the Sierra. The lower elevation of the montane conifer zone to the west is invaded by mixed evergreen and hardwoods, which move upward in elevation and into Yosemite Valley and the Tuolumne River canyon above and below Hetch-Hetchy. In general, the montane conifer type expands upward in elevation and further east towards the Sierra Nevada crest while contracting its lower range to the west. Small incursions of chaparral are interspersed more abundantly in the western part of the study area than in the historical map. In the mid-elevations of the montane conifer forest, chaparral and mixed evergreen woodland establish over broad expanses. Sagebrush appears in the southern part of Yosemite in isolated patches. Drought-tolerant species, such as hardwoods, chaparral and sagebrush, are generally more abundant.

Overall, 55% of the cells change vegetation class compared to the simulated baseline. The projected warming results in a transition from subalpine forest to montane conifer forest (25% of study area) and from montane conifer to mixed evergreen forest (13%) (Figure 10b). Fire allows chaparral to invade montane conifer and subalpine forest over roughly 6% of the area (Figure 10b).

MIROC A2 Scenario

The A2 Scenario, the hottest and driest scenario, is characterized by very large shifts in vegetation in all parts of the study area (Figure 11a). The predominant pattern is an upward shift in elevation of all vegetation types, and a loss of the highest elevation vegetation types. The alpine dwarf shrub and subalpine forest zones completely disappear. What was, originally, the alpine vegetation zone changes to a montane conifer forest zone. What was, originally, the subalpine forest zone changes to a montane conifer forest, montane chaparral, and mixed evergreen woodland. The lowest extent of the montane conifer forest is generally replaced by evergreen woodland and chaparral. Yosemite Valley and Hetch-Hetchy regions become predominantly mixed evergreen forest, interspersed with grassland and chaparral. In general, chaparral, mixed evergreen forest, and hardwood forest dominate the western parts of the Park below 8,000 feet (2,440 m). Chaparral and hardwoods dominate the western border outside the Park and have moved across the Park boundary and well into the western Park regions. Mixed evergreen woodlands are more prevalent within the Park. Conifer woodlands are simulated in the southeastern part of the Park at the highest elevations and also across the crest of the Sierra Nevada. The eastern part of the Park is simulated as montane conifer forest, which transitions eastward to chaparral and to interspersed woodland at the lower elevations especially outside the Park boundary, indicating a response to increased drought.

Overall, 68% of the cells change vegetation class compared to historical conditions. Warming drives most of the changes, but fire is important as well. Following MC1 model rules, the change from subalpine forest to montane conifer (18% of the study area) and the replacement of montane conifer (17%) with mixed evergreen forest are both entirely a result of warming thresholds. Montane conifer (3%) and subalpine forests (7%)

are replaced by mixed evergreen woodland, as a result of both warming and fire thresholds. Chaparral replaces 5-8% of the conifer vegetation types, as a result of fire thresholds (Figure 11b). Fire acts as a catalyst for vegetation change as accumulation of fuel and dry conditions cause fires to occur. Regrowth after fire in the model favors life-form assemblages better adapted to the new warmer and drier conditions.

Shifts in vegetation summary

The major potential vegetation shifts over the next century that are common to all three climate change scenarios examined (Figure 12a, b) include loss of the alpine dwarf shrub type, biomass decreases or loss of subalpine forest, biomass increases in the mixed evergreen forest and woodland, hardwood forest, hardwood woodland, and montane chaparral. The biomass increases are seen in vegetation types that generally do better under drought stress (Figure 12b). Especially large gains in biomass of these types are seen in the A2 scenario.

Scenario-dependent changes include, most significantly, the biomass of montane conifer, which decreases by 21% under both B1 and A2 emission scenarios, but increases by 21% under A1B. The greatest biomass of the study region is seen in subalpine forest and montane conifer (Figure 12a). The loss of the subalpine seen in the A1B and A2 scenarios represents a significant loss of overall biomass under those scenarios, which is only partly restored by the montane conifer forest which replaces it.

The largest shifts in potential vegetation type are further analyzed showing annual fluctuations (Figure 13). Changes in vegetation can be separated into those that are caused by exceeding an empirical temperature threshold for a given vegetation type in the model, or those that are triggered by fire events, which are a combination of biomass available to burn (fuel load) and dry conditions (fuel moisture or lack of). The steady decline in subalpine forest over the 21st century is driven by temperature. Montane conifer forests show initial gains in all scenarios through 2075. From then on, they sustain large declines with chaparral replacement through fires under the A2 emission scenario, moderate losses to chaparral also through fires under the B1 emission scenario, and the least losses to chaparral under A1B. Montane conifer forests under A2 are replaced by both montane chaparral and hardwood forests, particularly evident in two large fire periods around 2075 and 2095 (Figure 20). Here, significant drops in the extent of montane conifers are linked with the expansion of more drought- and heat-tolerant vegetation types. Under B1, similar large fire-driven transitions occur from the montane conifer type to the chaparral type around 2080 (Figure 13).

Carbon

Net Primary Productivity

Annual net primary productivity (NPP) represents the total carbon captured for the entire park region (minus plant respiration). It reflects the ability of plants to utilize the energy from the sun, given limitations in light, water, temperature and nutrients (Figure 14a). Over the 21st century, NPP declines were greatest under the A2 emission scenario. The drop in NPP reflects the decline of plant carbon uptake in this scenario, as lower overall biomass chaparral and hardwood ecosystems replace conifer forests (Figures 16,

18). Under scenario A1B, NPP shows a similar decline until the 2050s, when NPP rebounds as a consequence of a confluence of warmer temperatures (Figure 4a) but also greater winter precipitation (Figure 5a, Figure 16). A1B NPP levels out and remains fairly constant until the end of the century. NPP under B1 shows slight increases over historical NPP and maintains elevated levels compared to the other scenarios throughout the 21st century. None of the scenarios show long-term increases in NPP over the next century, as have been shown at the larger scale in California (Lenihan et al. 2003) under different future climate change conditions.

A well-documented response to increased atmospheric CO₂ is an increase in belowground root production in relation to aboveground shoot growth (Waring and Running 2007), as plants compensate for water and nutrient limitation by exploring larger volumes of soil. At the ecosystem level, aboveground biomass losses to fire can also decrease the ratio of above to belowground NPP. Under all scenarios this ratio declines significantly after the 2050s (Figure 17), but most dramatically under the A2 emission scenario. The timing of the decline under A2 is concurrent with increases in fire-related vegetation changes. The root to shoot production ratio under A1B and B1 declines gradually over the 21st century, until late in the century when even larger declines are observed over a short period (Figure 17).

Net Ecosystem Productivity

Net Ecosystem Productivity (NEP) is a measure of carbon accumulation in plant and soil elements of the ecosystem. When conditions are stable, NEP is close to zero. When soil respiration exceeds plant production, the system loses carbon while when production exceeds decomposition the system sequesters carbon. NEP declines with biomass loss (eg. to fire) and soil disturbance. It is a good index of environmental conditions. NEP shows strong interdecadal variations under the various future climate scenarios (Figure 14b). After the 2050s, the amplitude of the NEP swings becomes greater as a result of larger ecosystem disturbances. NEP decline is greatest under the most extreme A2 scenario.

Net Biome Productivity

Net Biome Productivity (NBP) includes the impacts of fire in the overall carbon budget. Under all scenarios, NBP becomes increasingly more negative over the 21st century (Figure 14c). Carbon losses from fire make this region a net carbon source, with the potential to create a positive feedback to the warming climate. Worst NBP losses are under the warmest A2 emission scenario. It is important to note that NBP also show large decadal variations throughout the century with various-amplitude cycles of fire losses and recovery but that the general trend is downward towards net losses by the end of the century. MC1 simulates only fire out of all the possible disturbances (insects, windthrow, etc.). Since other disturbances are omitted, the loss of carbon from disturbance may be underestimated, and consequently the NBP may be overestimated.

Summary of carbon dynamics

A2

In summary, warm temperatures and dry conditions support the expansion of vegetation types with higher drought tolerance and lower productivity – smaller, sparser

stands with higher potential losses to fire – at the expense of forest types with high productivity and historically experiencing less frequent fires. These changes result in large decreases of total vegetation carbon, extensive losses to fire, resulting in net carbon losses to the atmosphere at the biome level over the 21st century.

A1B

Despite widespread expansion of the montane conifer forest type, the region is expected to experience significant carbon losses by the end of the century. Some recovery is simulated shortly around the 2050s but continuous warming contributes to more losses until 2100. Moderate fire frequencies under this future scenario prevents the area from experiencing the extent of carbon losses simulated under A2, however the general result is also a net loss of carbon to the atmosphere.

B1

The B1 scenario maintains conditions closest to historical, with fairly stable trends in NPP and NEP over the 21st century. Only an increased frequency of fires by the last quarter of the century causes a decline in NBP and total vegetation carbon. Perhaps another hundred years would show bigger changes, but this scenario shows the smallest changes of all the scenarios.

Fire

Fire emissions

Overall emissions from fires increase dramatically in comparison with historical conditions (Figure 19). The model predicts that, under the warm and dry A2 emission scenario, emissions from fires will increase over 6 times from historical levels. Fire emissions with the moderate warming simulated under the A1B emission scenario are predicted to be 3.5 times greater than historical means. Even under the B1 emission scenario with the least warming and a slightly wetter climate, emissions are predicted to more than double as compared to historical levels. Under all future scenarios, the bulk of the emissions occur as CO₂ that is released through the combustion of live or dead stems and leaves. The increase in fire indicates that more fuels are able to burn due to an increase in water deficits under the three scenarios. The greater the water deficit as the scenarios proceed from B1 to A2, the higher the frequency of fire, the greater the total area burned, and the greater the emissions.

Fire frequency and area

An increase in fire frequency and area burned is expected under future conditions that are hotter and drier (Figure 20). The area of the park where there is some fire activity is projected to generally increase under all three emissions scenarios. There is however significant year-to-year and decadal variability in fire occurrence (Figure 20). There is a statistically significant upward trend in area burned over time only under the A2 emission scenario. A pattern of higher than normal fire years during normal to drier than normal seasons that are preceded by one or more wetter than normal years has been documented in the U.S. southwest (Swetnam & Betancourt 1998). The fire module in MC1 does not

simulate fire ignitions (lightning or human), but applies fire to a cell when live and dead fuels exceed dryness and biomass thresholds assuming ignition sources are never limiting.

Table 5: Paired comparisons of mean annual area burned (hectares) under the last 30 years of the historic period and of the three future climate and emission scenarios. Student's T-test were performed on log transformed values (actual values presented). Values containing the same letter are not significantly different.

Simulation	Mean Area Burned (ha)	Standard Deviation	Significance
A2	12,229	26,312	A
A1B	6,595	14,155	AB
B1	4,859	17,547	BC
Historical	2,075	3,194	C

When comparing the last 30 years of the simulated historical period and of the three future scenarios, mean annual area burned increases from a historical average of about 2,000 hectares up to almost 5,000 hectares under the B1 scenario, to 6,600 hectares under the A1B scenario, and to over 12,000 hectares under the A2 scenario. This is a dramatic increase in area burned and illustrates the degree to which predicted future climate conditions are likely to alter fire regimes. Comparing the last 30 years of the 21st century with the last 30 years of the historical period (log transformed to smooth the signal) shows significant differences among means ($F_{3,116} = 6.59$; $p < 0.0004$) (Table 5).

The warmer and drier the predicted climate, the greater the area within the park that will burn annually. Under the worst case scenario (A2), annual area burned by the end of this century will be six times the simulated historic average. Average annual area burned increases from the B1 scenario up to the A2 scenario due to a progression in the severity of conditions favorable to burning (Figure 20).

Fuel loads

Fuel loads for the study area are slightly less under all three future climate scenarios compared to the historic data (Figure 21) and represent a decrease in biomass due to drought stress and/or a net increase in fire under future climate. The A2 scenario with the most warming and largest increase in area burned shows the most decrease in fuels over the historical baseline though the decrease is not large. The increased fire frequency and area burned under this scenario burns up much of the available fuel loads for all size classes. However, although total fuel loads do not decrease much compared to baseline historical levels, there is a rearrangement of the partitions into the fuel size classes. The hotter the future scenario and the higher the incidence of fire, the greater the loss in large fuel sizes (1,000 h) and the greater increase in the smallest fuel size (1 h). This likely represents a decrease in large tree density and cover and increases in woodland area, the relative fraction of small sized trees, and area covered by shrublands in response to the increase in fire frequency.

Fire index

The fire index value is the ratio of biomass consumed by fire to NPP (TgC/TgC) over the final thirty-year period of this century, and thus an indication of how fire-prone that grid cell is. Our fire index maps (Figure 22) show the greatest fire-mediated carbon losses where dry conditions overlap with large fuel loads (B1 and A1B). Under the B1 emission scenario, the highest fire-mediated carbon losses are in areas which have converted from historically montane conifer to chaparral, thus are drought-stressed areas embedded in a montane conifer type, on the western and eastern edges of the Sierra Nevada slopes. The long-term trend is for a decrease in fuel load as large trees are replaced by shrubs but stressed or dying conifers will provide a ready source of shorter-term fuel load. Under the A1B emission scenario, the greater fire-mediated carbon losses are on the western slopes where drought stress is more likely and favors the expansion of chaparral. Under the A2 scenario both eastern and western slopes of the Sierra Nevada are at risk of losing a large fraction of their sequestered carbon to fire, corresponding roughly to 2/3 of the study area. Results from the three future scenarios all agree at mid-elevation on the western side of the Sierra crest, which may therefore be the region with the greatest likelihood of fire-mediated carbon losses during this century.

Uncertainty

Uncertainty in modeling results arises from various sources. Vegetation model results depend greatly on the reliability of the input data used to run the model. Initially, 3 emission scenarios and 3 climate models were chosen to bracket a range of potential future climate based on available gridded time-series datasets (IPCC 2007). Uncertainties in scenarios have been and continue to be discussed at length and this effort will not be repeated here (eg. Giorgi et al. 2001, IPCC 2007). We will however mention that downscaling climate anomalies from coarse-scale GCMs to a topographically complex landscape like Yosemite National Park, adds yet further uncertainty in the outcome (eg. Giorgi et al. 2001, Daly 2007). It is clearly beyond the scope of this report to tackle these kinds of uncertainties.

Another form of uncertainty lies in the likelihood of any given scenario's outcome. The Yosemite study included only 3 future climate scenarios, and those 3 were chosen to span the range of 9 scenarios for which we had data. There is no way to know what the future will actually be like, nor which of our three future climate scenarios will turn out to be most similar to the real climate of the 21st century. But each of the scenarios is plausible, and so we conclude that the range of plausible future vegetation shifts is at least as large as the range spanned by the modeled outcomes from the 3 scenarios.

Uncertainty from vegetation models also comes from the MC1 model itself. MC1 was designed to capture coarse scale processes and does not include local features that can greatly affect the reliability of its results such as riparian conditions and erosion/sedimentation processes that affect soil depths across the park. It simulates potential vegetation, whereas the park vegetation has been significantly changed from "natural" in a number of areas due to human influences. The model does not include explicitly any animal impacts such as grazing, browsing, insect damage which affect plant growth and establishment. The model does not simulate dispersal nor seedling establishment and while van Mantgem et al. (2009) have reported increased mortality in western states and inside YNP, their mortality rates are still within historical range but

the recruitment values they measured are significant below historical records. Finally, MC1 was run on a new climate dataset at a resolution it had not been run before. While the fire model had been “improved” for regional analyses for other projects, we have found some of its changes to negatively affect our simulation of fine scale processes. The fire model which once focused on stand-replacing fires is now simulating frequent low intensity fires.

Next Steps

Further analysis of the model results and the generation of publications are planned as a part of a follow-up for this study. The study, as proposed and funded, has raised many interesting questions and promising avenues of further investigation. Such areas include:

- This report included results from an in-depth analysis of historical vegetation distribution maps, as well as reconciliation of the Wieslander data and the Yosemite 1997 Survey with the CALVEG dataset in collaboration with Jim Thorne (UC Davis). While this was outside the scope of work initially proposed, the increased scrutiny of the Yosemite data has significantly changed the assigned MC1 vegetation types of the Yosemite 1997 Vegetation Survey data. Future planned runs of MC1 may improve the relationship between MC1 and the updated Yosemite 1997 Vegetation Survey.
- The scale (grain) of the simulation has required a substantial recalibration of the biogeography rules and some biogeochemistry parameters. A detailed comparison of model results at 50 km, 12 km and 800 m for California will allow us to explain the loss/gain of information as results are presented at the state vs. park level.
- The creation of a new soil input dataset for the model based on the soil information provided by the park has not been used for any of the results presented in this report, but will be included in the publications that derive from this work.
- A detailed analysis of streamflow and comparison of simulated annual flow with gage data would allow calibration of the hydrological model. Furthermore, future collaboration with Christina Tague may improve the simulation of water flow and allow a model like RHESYS to inform MC1 that does not include cell to cell communication or ground water flow.
- The fire model has not yet been tested against the fire records provided by the Park Service. These observations include the impacts of Park-wide suppression efforts and will be used with caution.
- Uncertainty needs to be calculated and will be the subject of at least one publication deriving from this project.
- Thorough sensitivity analyses should be conducted to quantify the sensitivity of the model to a variety of its input. Again, the scale of the study has shown that the sensitivity of the model can also vary as a function of the level of detail included in its input.

Input from park personnel is welcome (even requested) to shape the content of the next iteration. We expect park collaborators will continue to work with us on some of the subsequent efforts that will develop. The publications that will be generated from this project will include them as co-authors and their active participation in the data analysis and interpretation is essential to ensure the quality of the products that will be submitted

to peer-reviewed journals.

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7. Figures

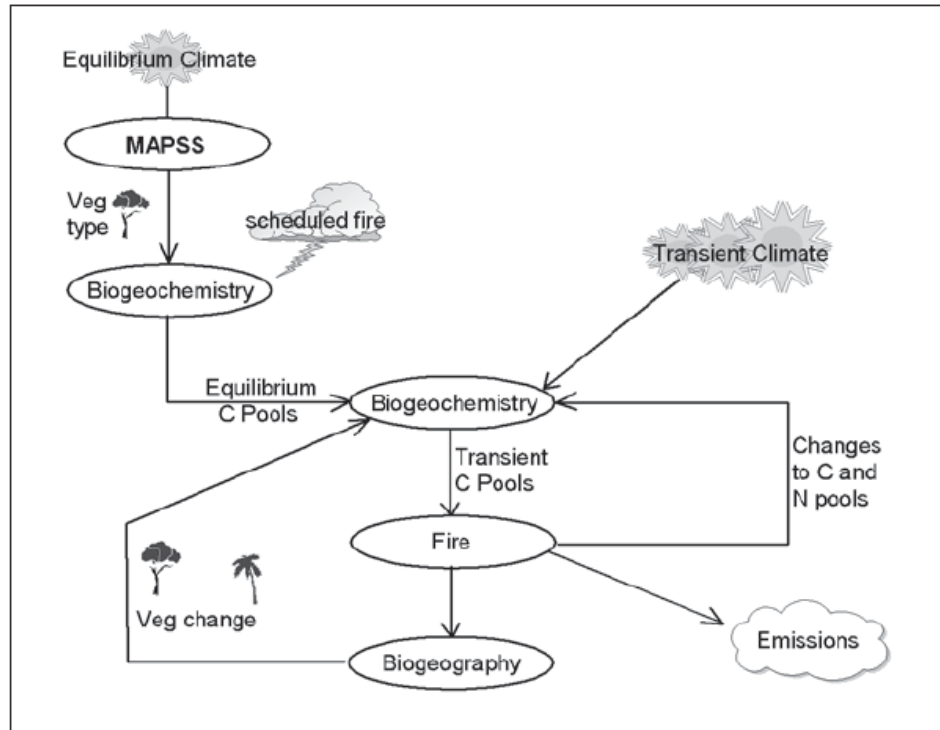


Figure 1. Cartoon representation of the MC1 dynamic global vegetation model and the connections between its 3 submodels focusing on biogeography, biogeochemistry and fire.

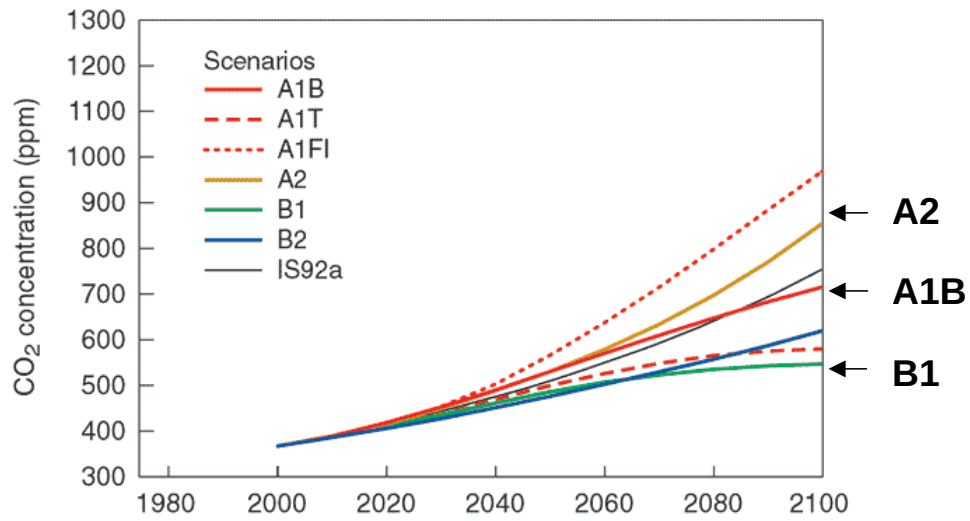


Figure 2. Projected atmospheric concentration of CO₂ as simulated for the IPCC Special Report on Emissions Scenarios (SRES, IPCC 2007).

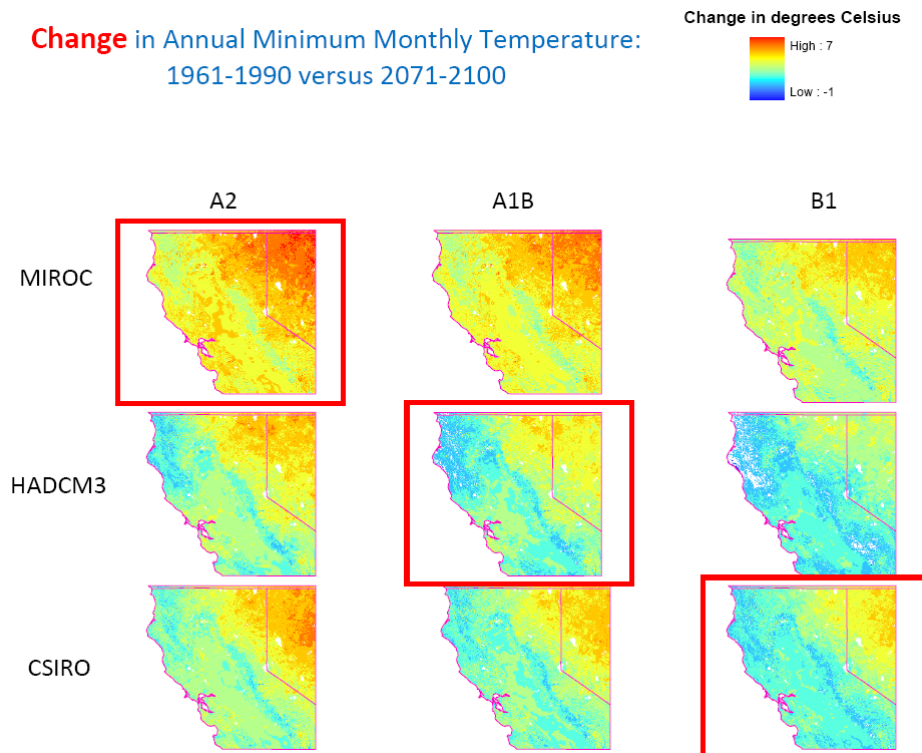


Figure 3a. Change in annual minimum monthly temperature for north-central California under 3 emission scenarios (columns) and 3 climate scenarios (rows) simulated by three general circulation models: CSIRO, Hadley and MIROC. The scenarios chosen for this study are highlighted in red (McGlinchy et al. 2008).

Relative Change in Annual Precipitation:
1961-1990 versus 2071-2100

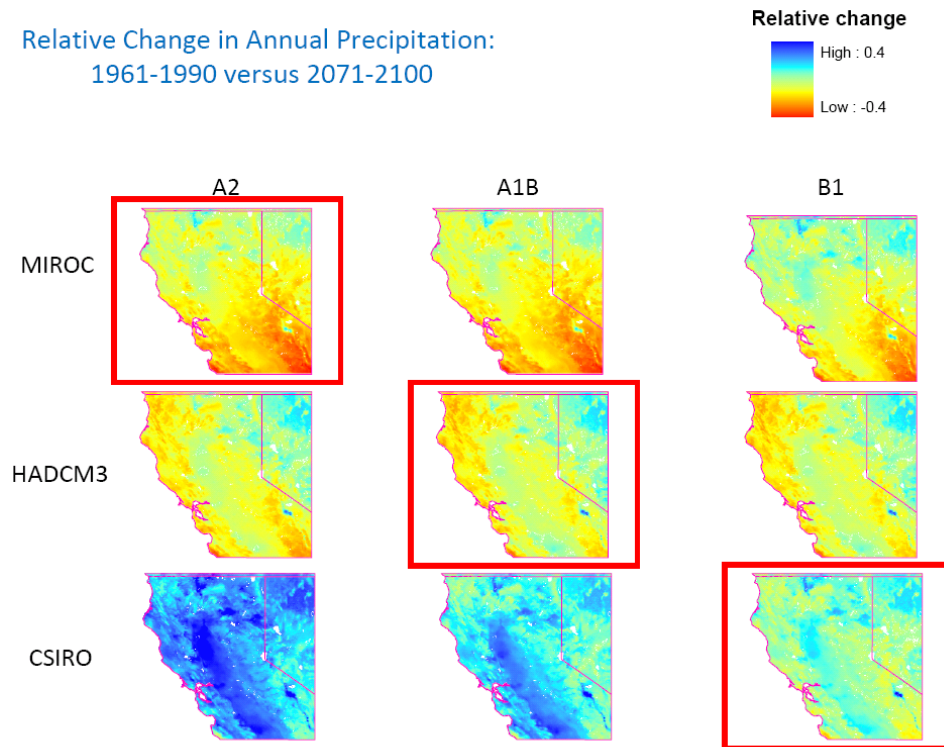


Figure 3b. Change in annual precipitation for north-central California under 3 emission scenarios (columns) and 3 climate scenarios (rows) simulated by three general circulation models: CSIRO, Hadley and MIROC. The scenarios chosen for this study are highlighted in red (McGlinchy et al. 2008).

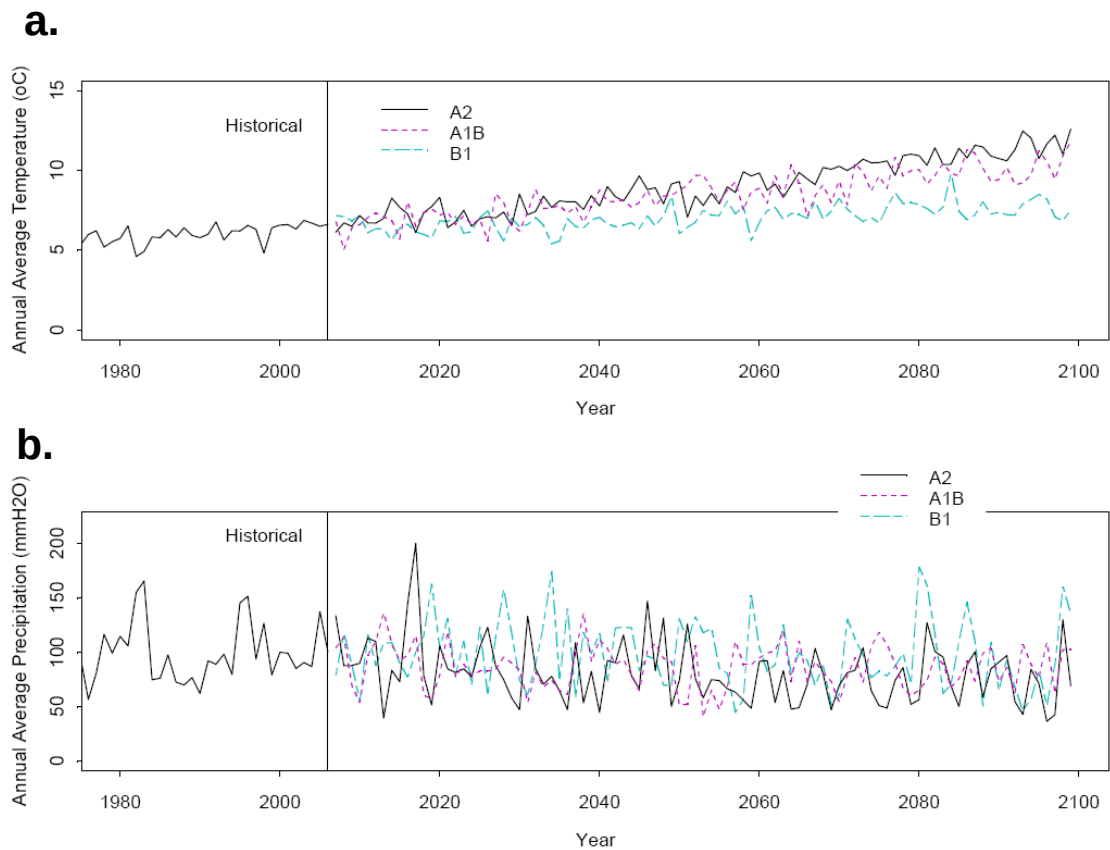
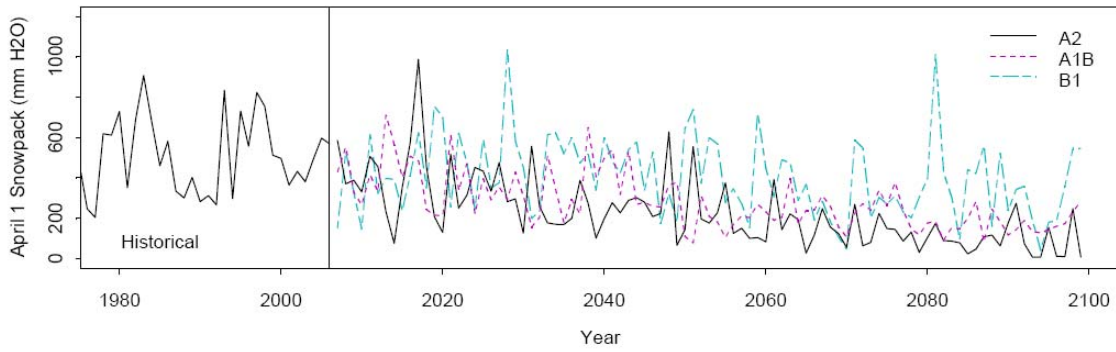


Figure 4. (a) Mean annual temperature and (b) precipitation at Yosemite National Park under 3 emission x climate scenarios, CSIRO B1, Hadley A1B and MIROC A2.

a.



b.

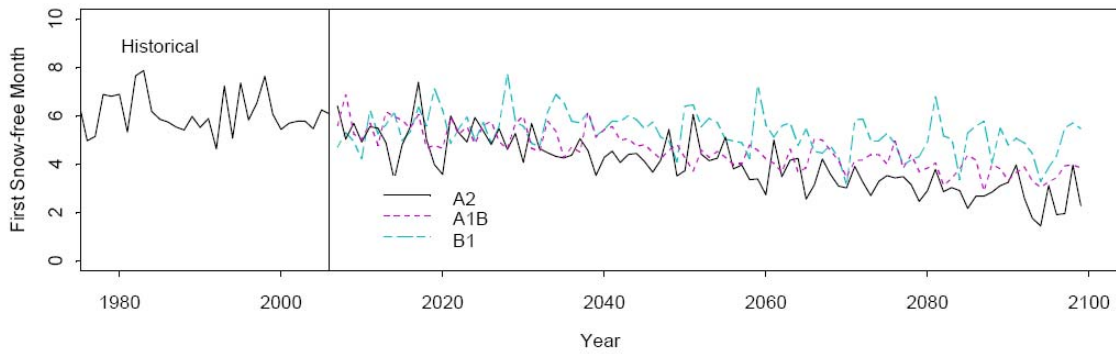
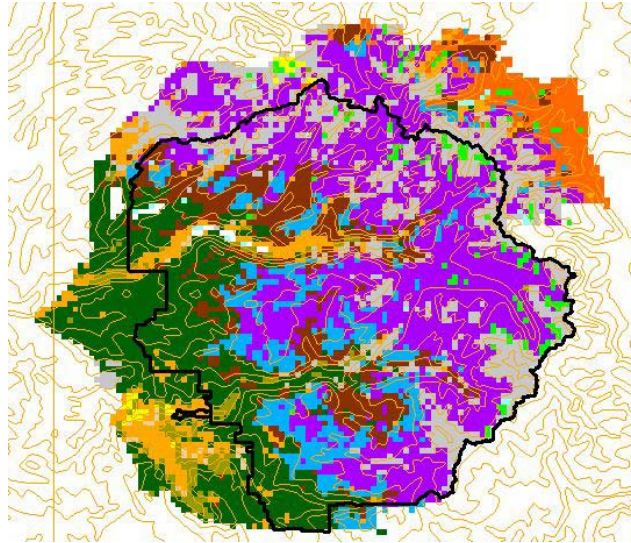
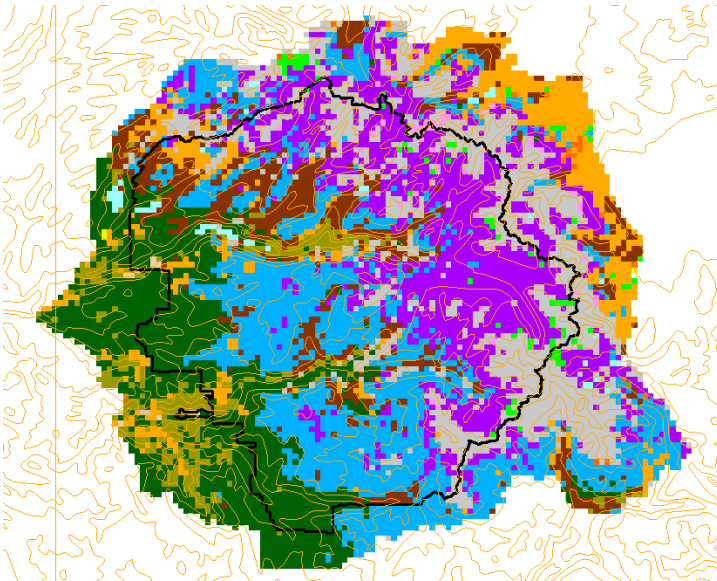


Figure 5. (a) Average April 1 snow-water equivalent and (b) average first snow-free month at Yosemite National Park under 3 emission x climate scenarios simulated, CSIRO B1, Hadley A1B and MIROC A2.

a.



b.



c.

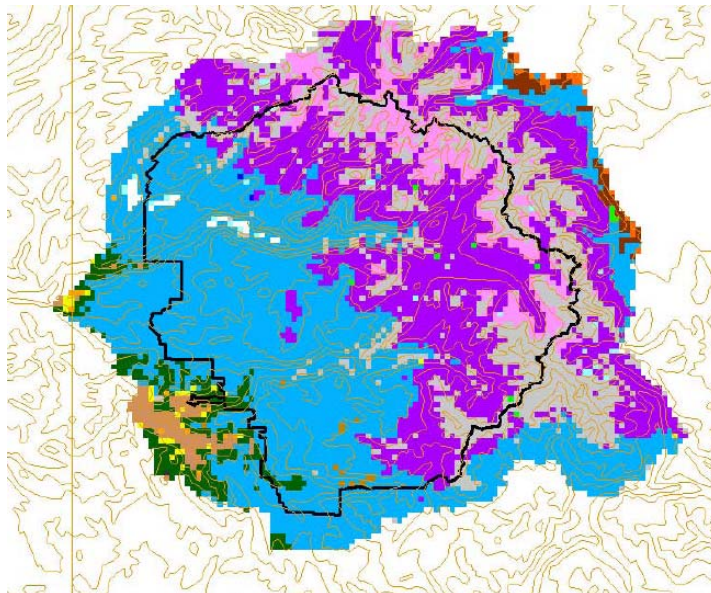


Figure 6. a. Observed vegetation from the 1920-1930's (courtesy of J. Thorne, UC Davis) referred to as "Wieslander" in the report (vtm.berkeley.edu/). b. Observed vegetation from the 1997 Yosemite Park survey (www.nps.gov/yose/nature/science/vegetation-map.htm) c. Simulated modal potential vegetation for the period 1987-96 (most frequent vegetation type simulated during the decade) by the MC1 dynamic global vegetation model for Yosemite National Park.

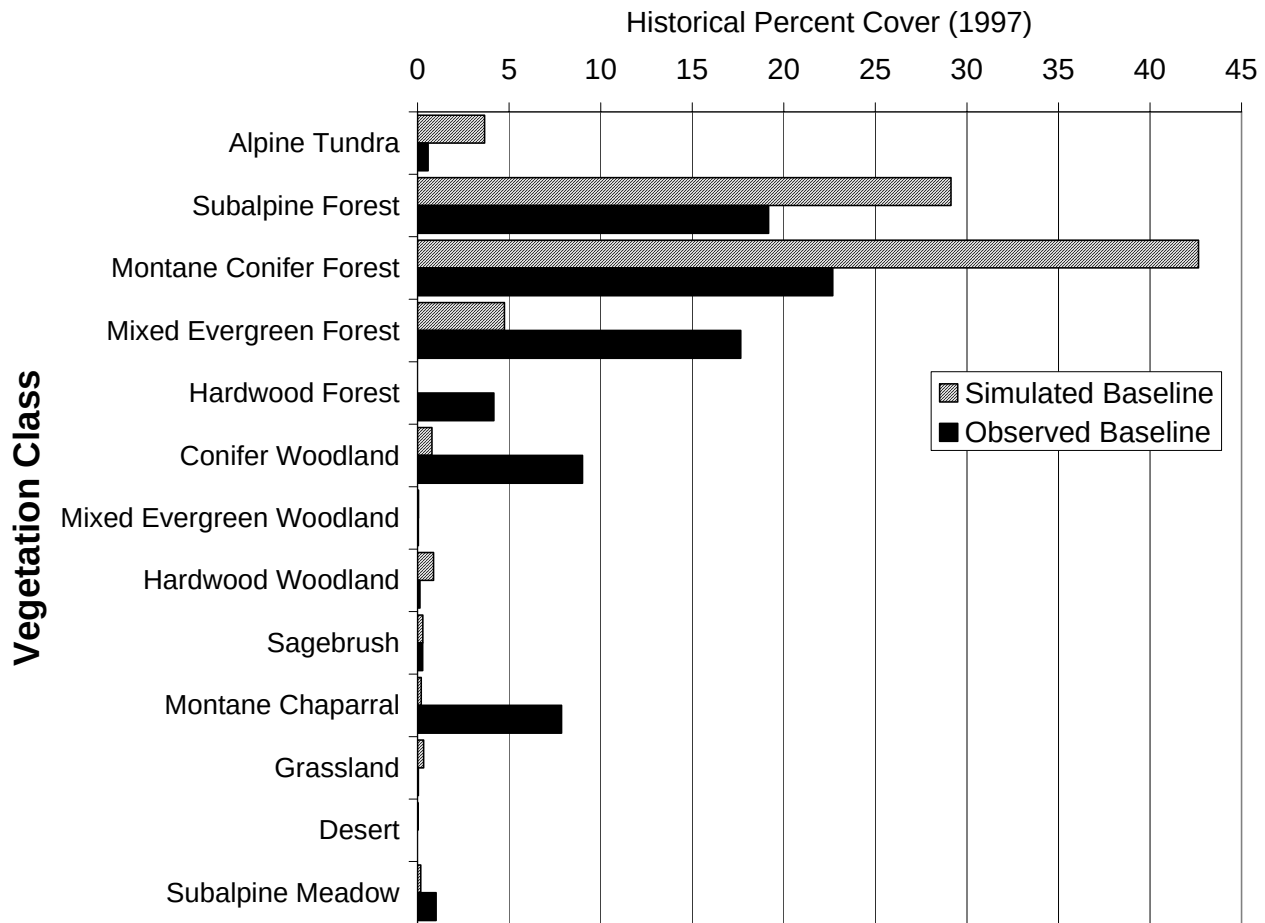


Figure 7. Percent cover by potential vegetation types (1986-1997 mode) as simulated by the MC1 dynamic global vegetation model compared to observed vegetation from the 1997 NPS survey data (<http://www.nps.gov/yose/naturescience/vegetation-map.htm>).

**Simulated
Historical**

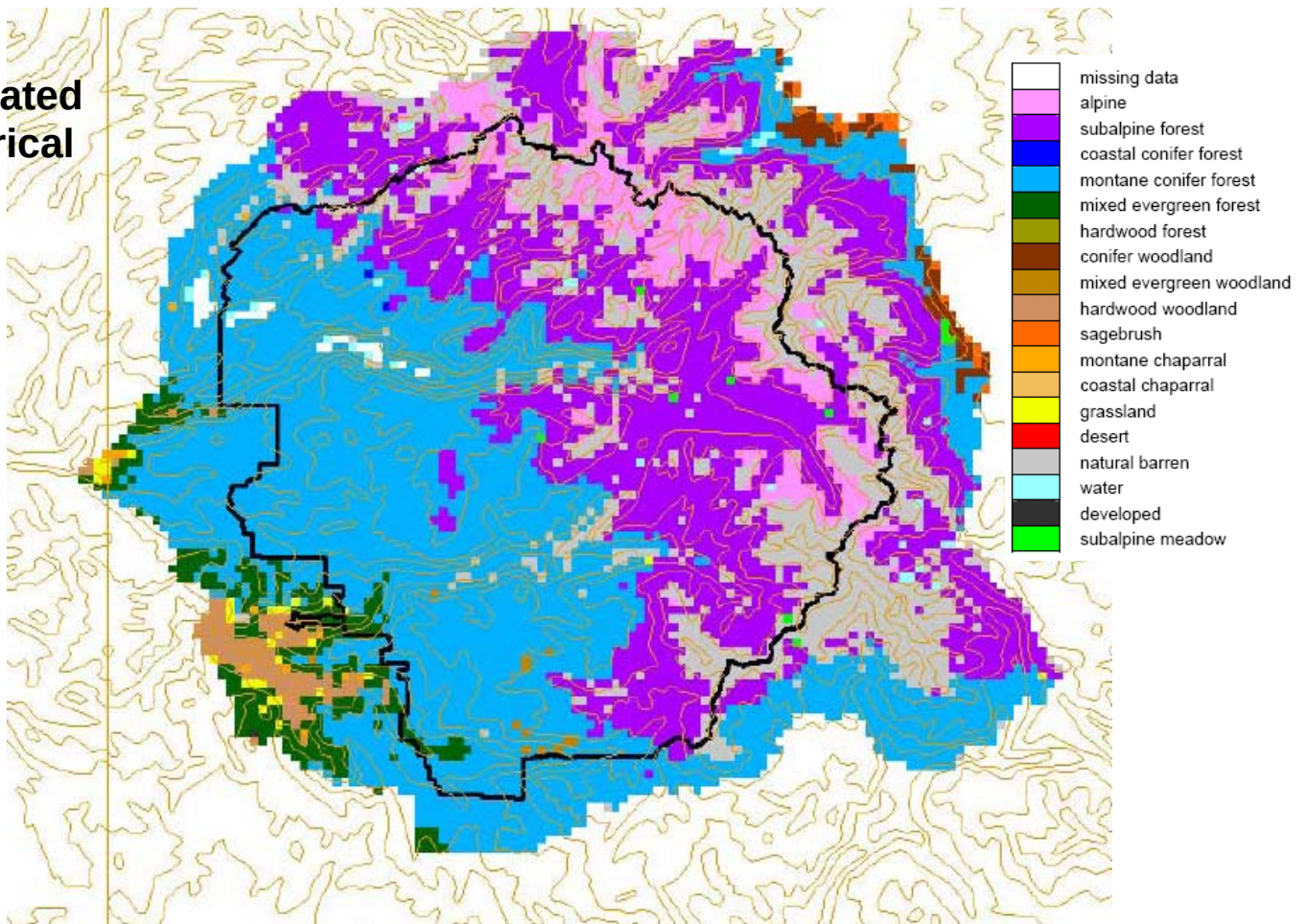


Figure 8. Modal vegetation types simulated by the dynamic global vegetation model MC1 under historical conditions for Yosemite National Park (most frequent vegetation type between 1987 and 1996).

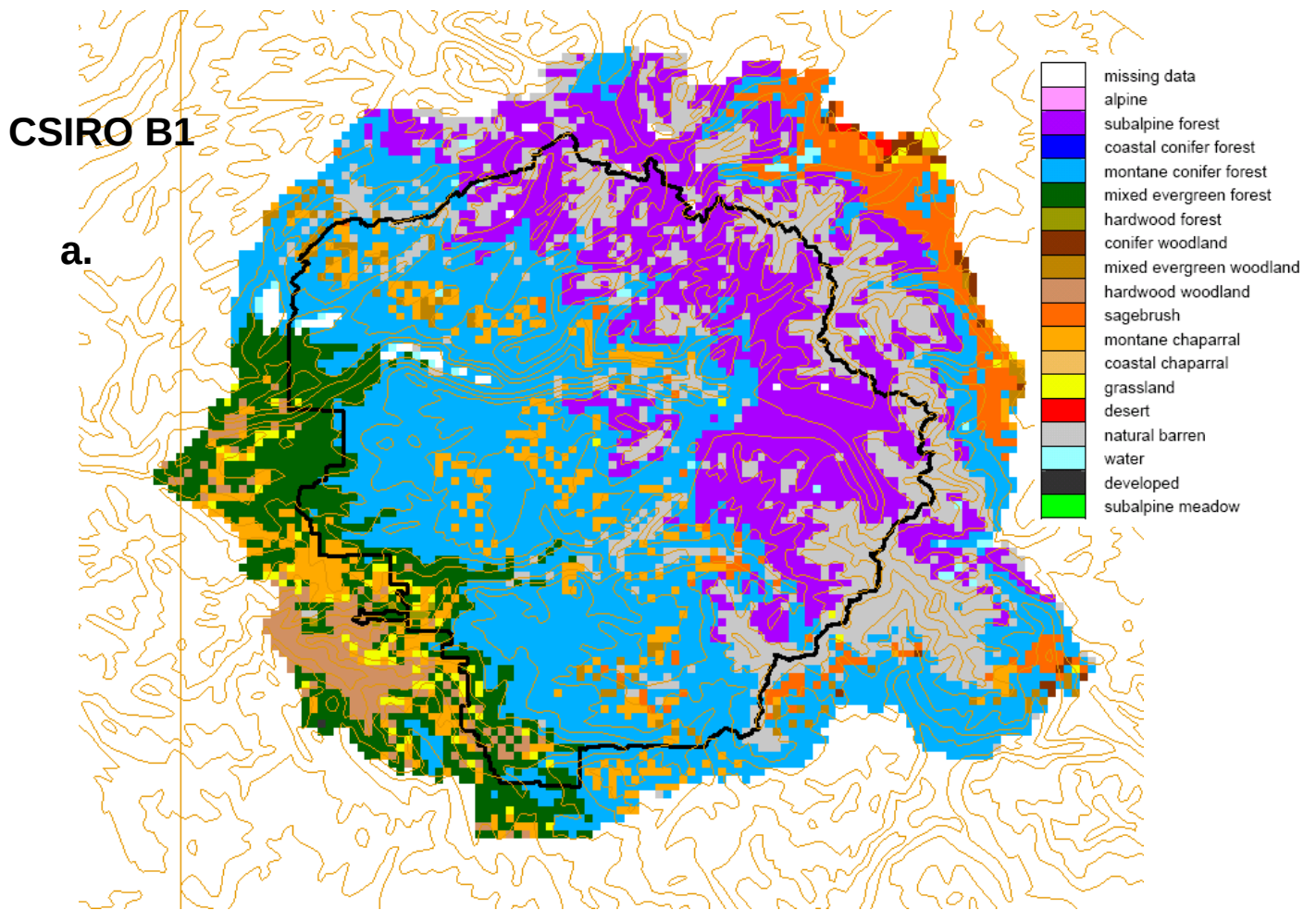
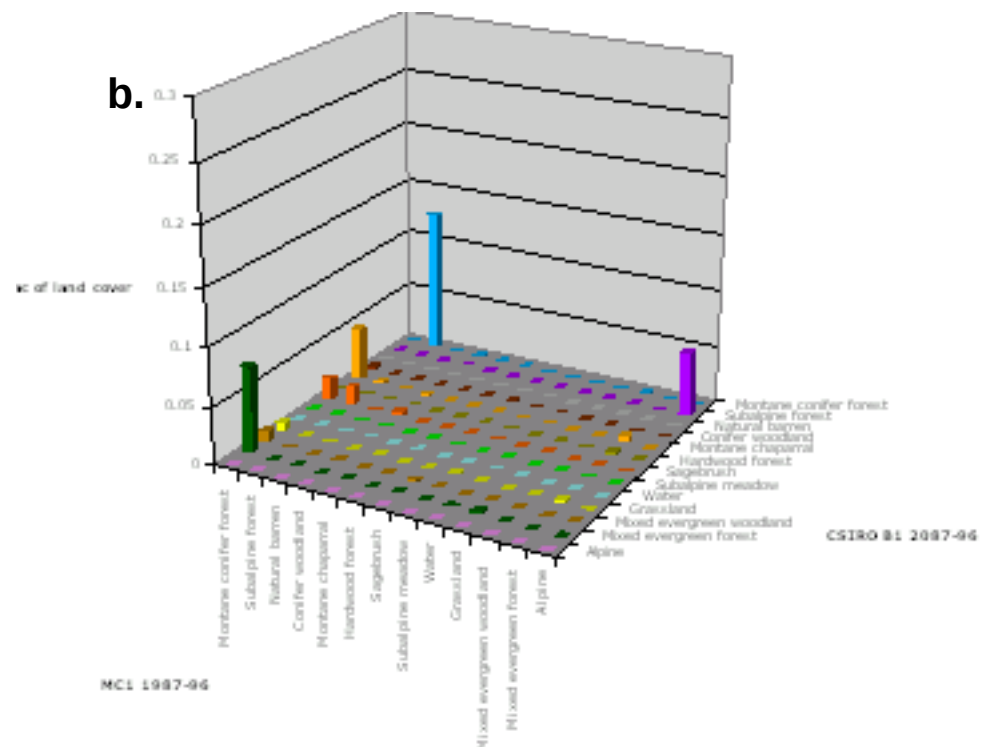
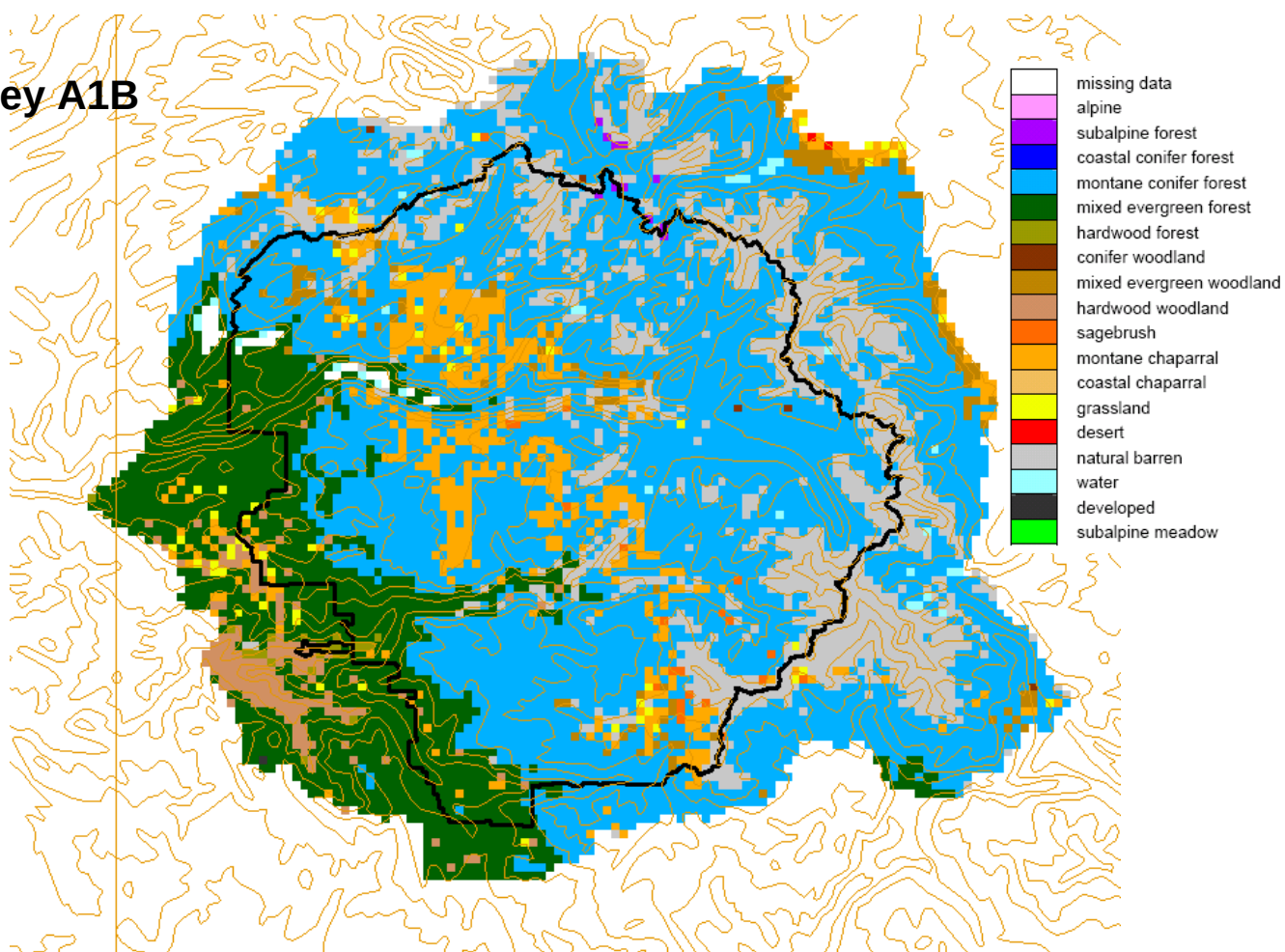


Figure 9a. Modal vegetation types simulated by the dynamic global vegetation model MC1 under the B1 CO₂ emission and CSIRO future climate scenario for Yosemite National Park (most frequent vegetation type between 2070 and 2100). 9b. Change in vegetation types comparing historical conditions (1987-1996) to CSIRO B1 (2087-2096).



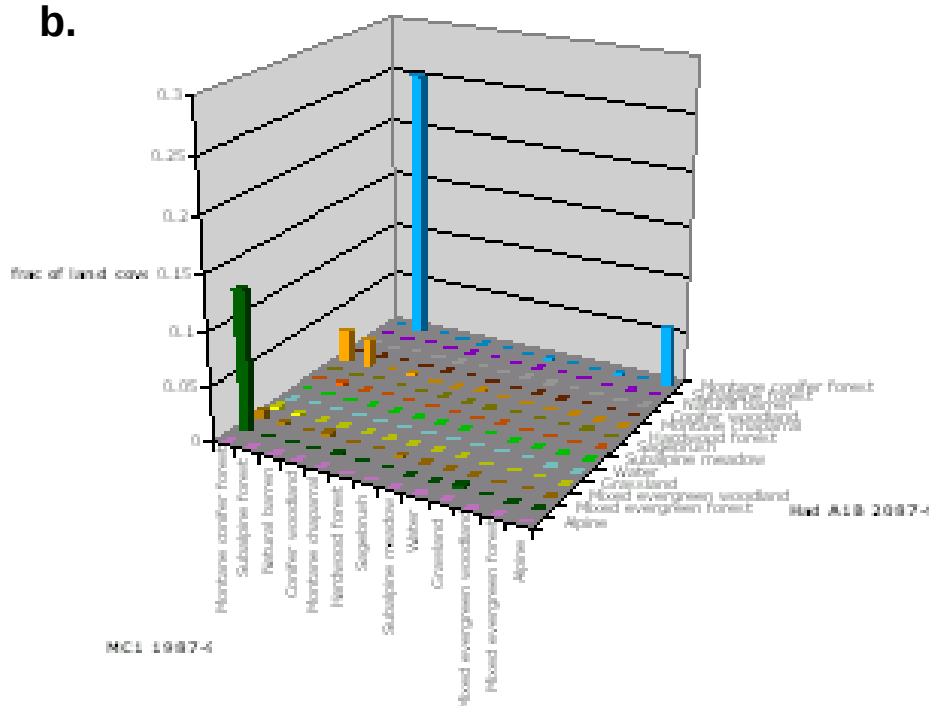
Hadley A1B

a.



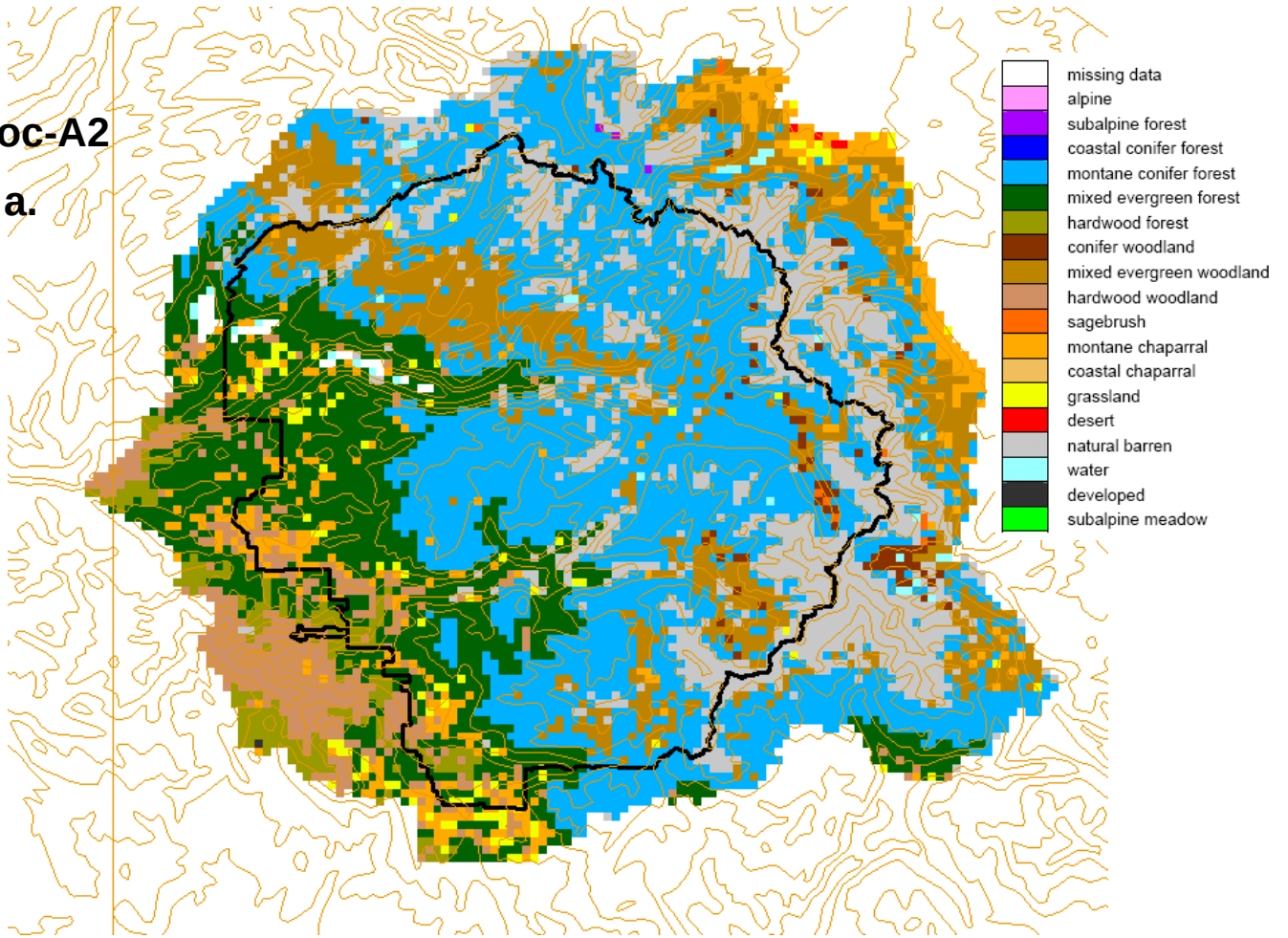
b.

Figure 10a. Modal vegetation types simulated by the dynamic global vegetation model MC1 under the A1B CO₂ emission and Hadley future climate scenario for Yosemite National Park (most frequent vegetation type between 2070 and 2100). 10b. Change in vegetation types comparing historical conditions (1987-1996) to Hadley A1B (2087-2096).



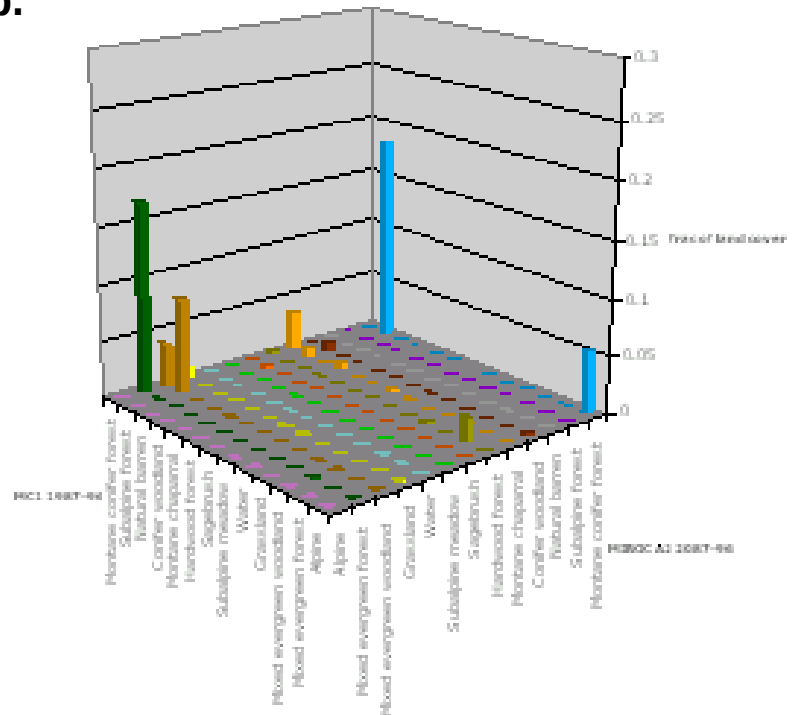
Miroc-A2

a.



b.

Figure 11a. Modal vegetation types simulated by the dynamic global vegetation model MC1 under the A2 CO₂ emission and MIROC future climate scenario for Yosemite National Park (most frequent vegetation type between 2070 and 2100). 11b. Change in vegetation types comparing historical conditions (1987-1996) to MIROC A2 (2087-2096).



a.

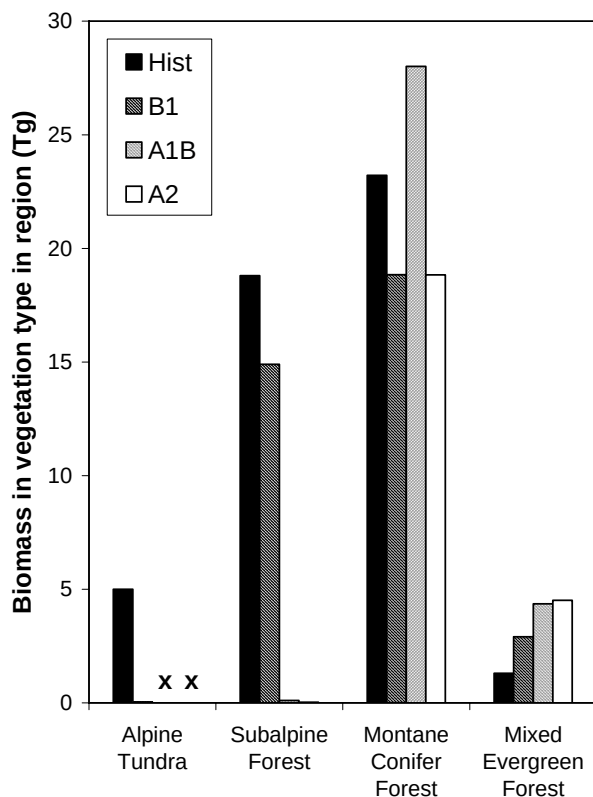
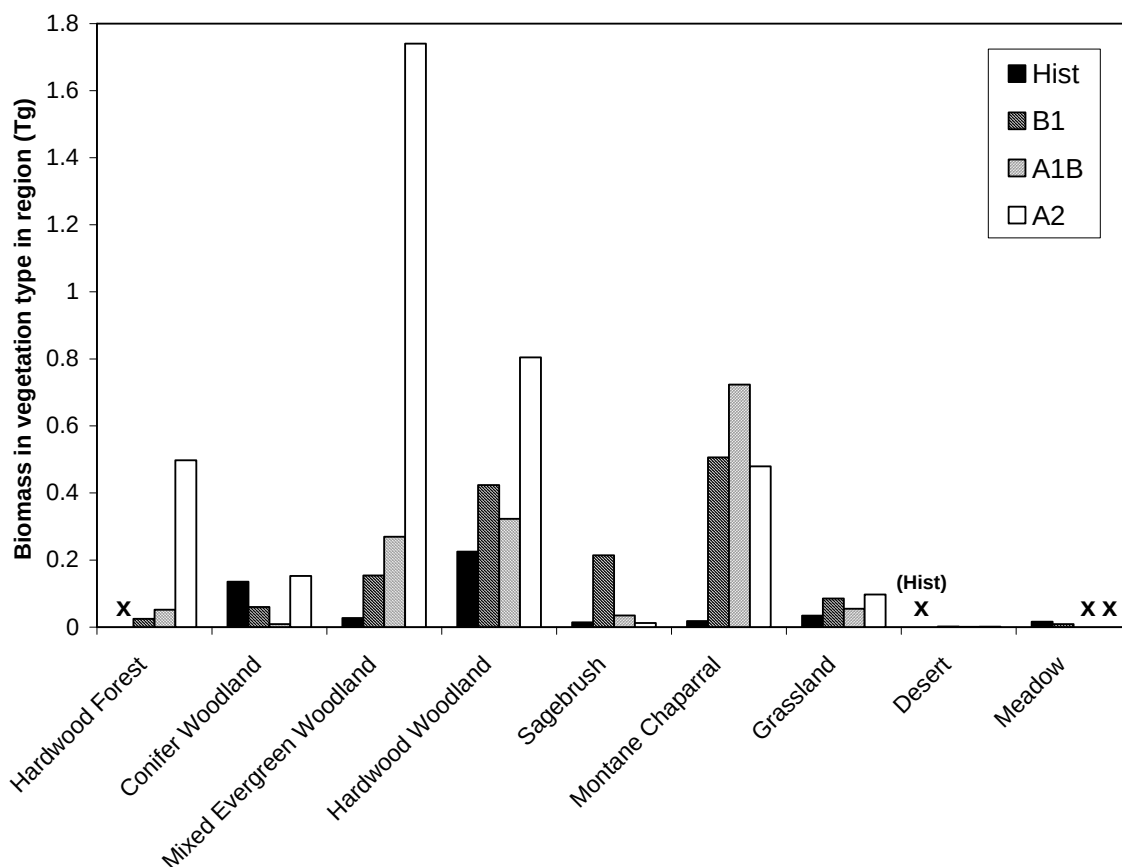


Figure 12. Total carbon (Tg) in vegetation type over the study region for 1987-1996 of the historical period compared to 2087-2096 of the simulated period, under 3 CO₂ emission scenarios at Yosemite National Park as simulated by the dynamic global vegetation model MC1. Vegetation types have been separated into large total carbon (a) and small total carbon (b) for ease of viewing. Note difference in scale. An “X” denotes no vegetation of that type in that scenario.

b.



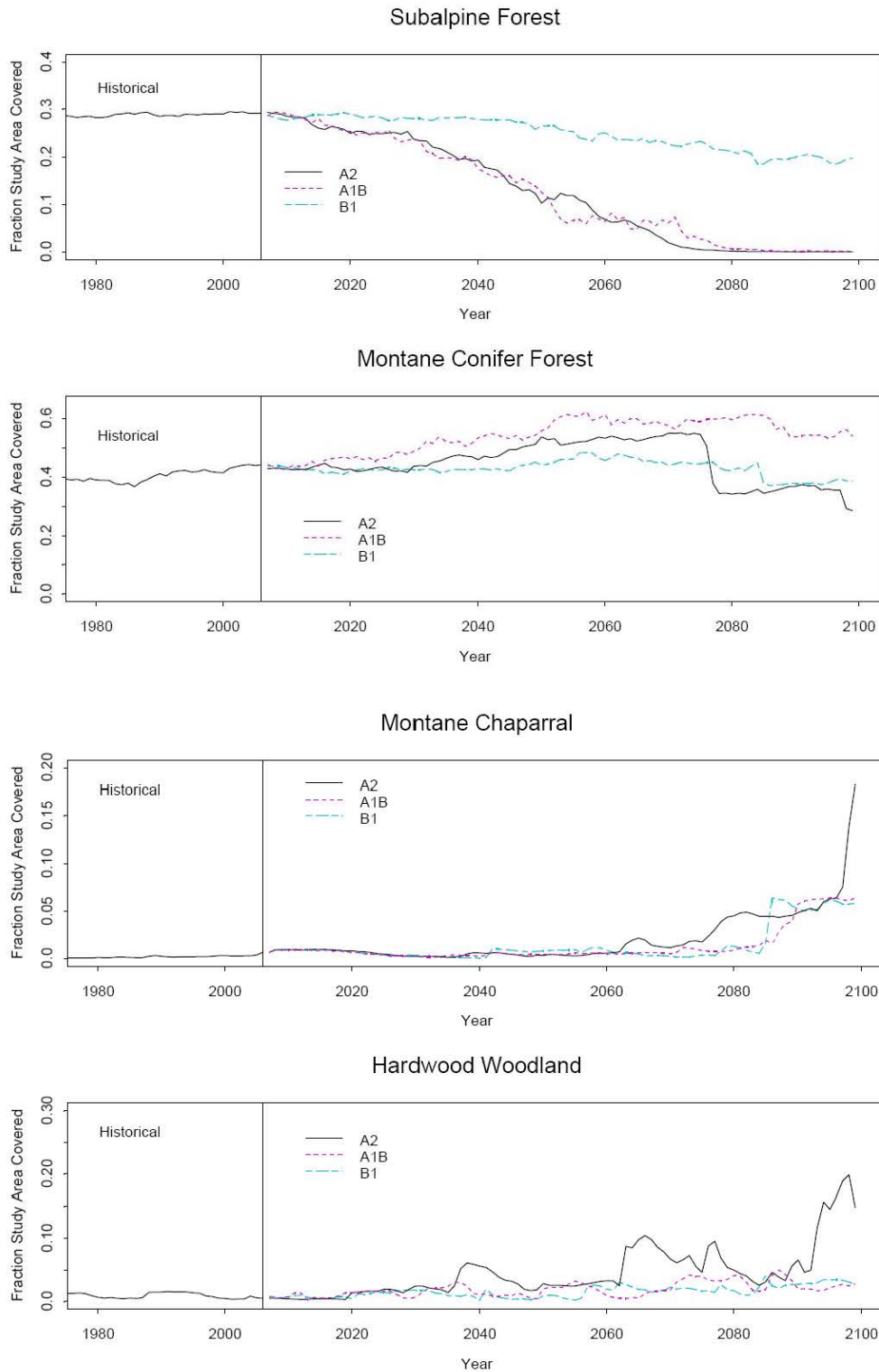


Figure 13. Area of potential vegetation classes that showed the greatest shifts under the 3 different climate and CO₂ emission scenarios simulated by the dynamic global vegetation model MC1 at Yosemite National Park.

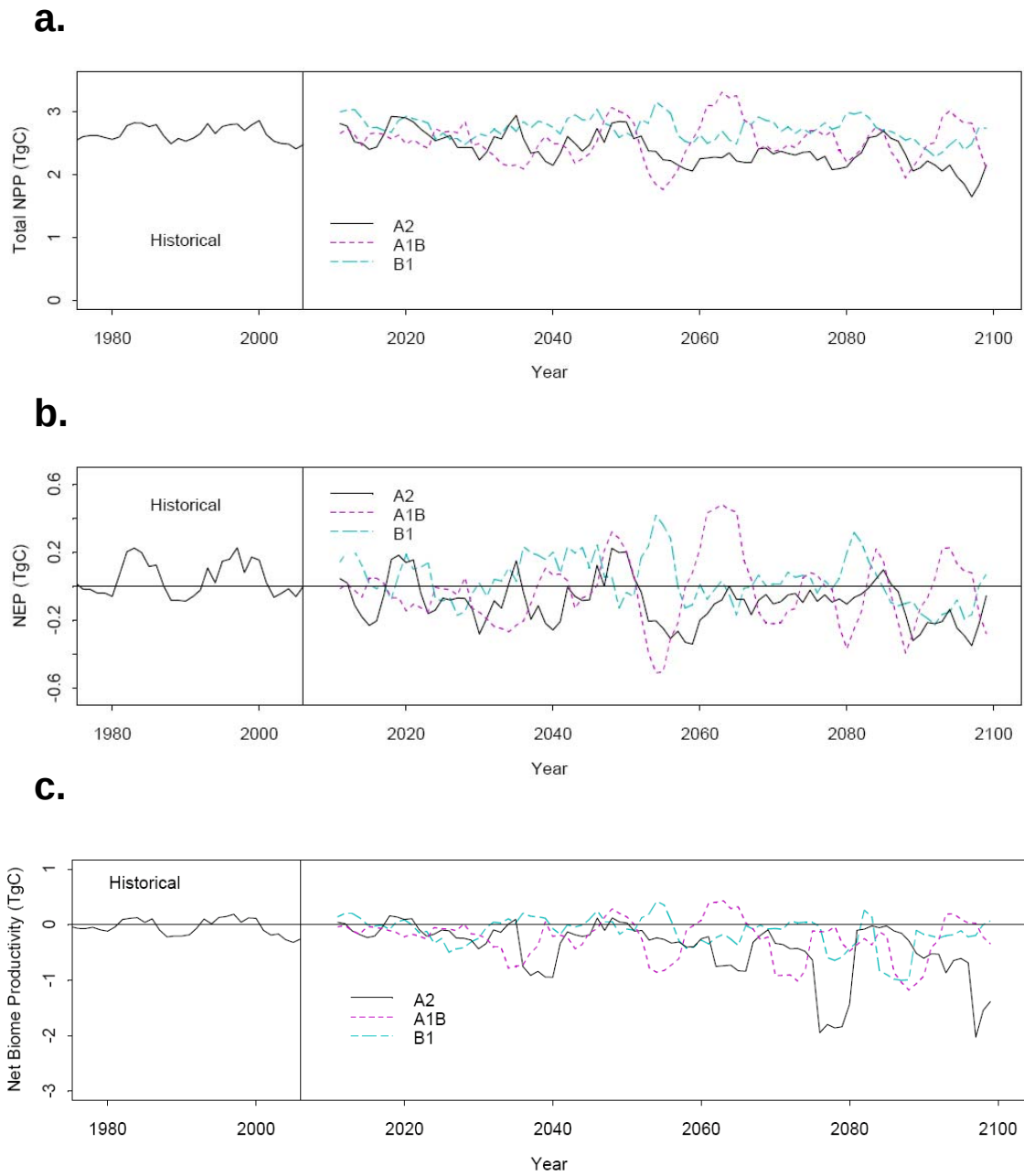


Figure 14. (a) Total net primary productivity (NPP), (b) total net ecosystem productivity (NEP), and (c) net biome productivity (NEP-carbon consumed by fire) simulated (5-year running average) by the dynamic global vegetation model MC1 under 3 different climate and CO₂ emission scenarios at Yosemite National Park. .

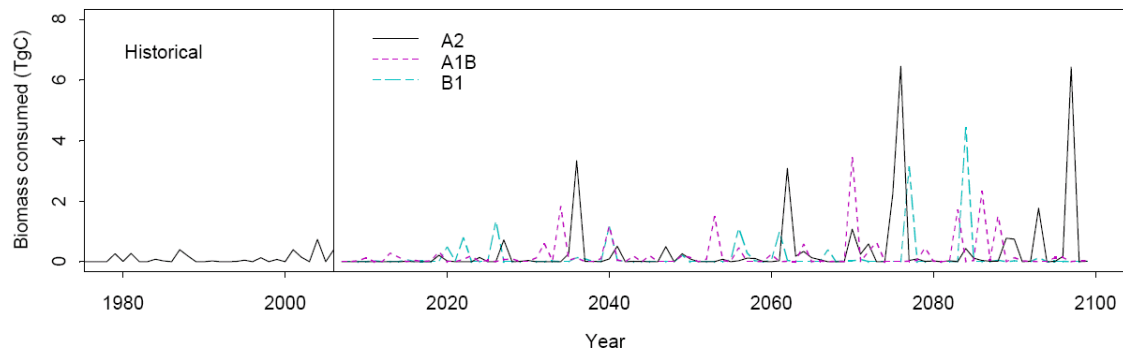


Figure 15. Biomass consumed by wildland fire as simulated by the dynamic global vegetation model MC1 under 3 different climate and CO₂ emission scenarios at Yosemite National Park.

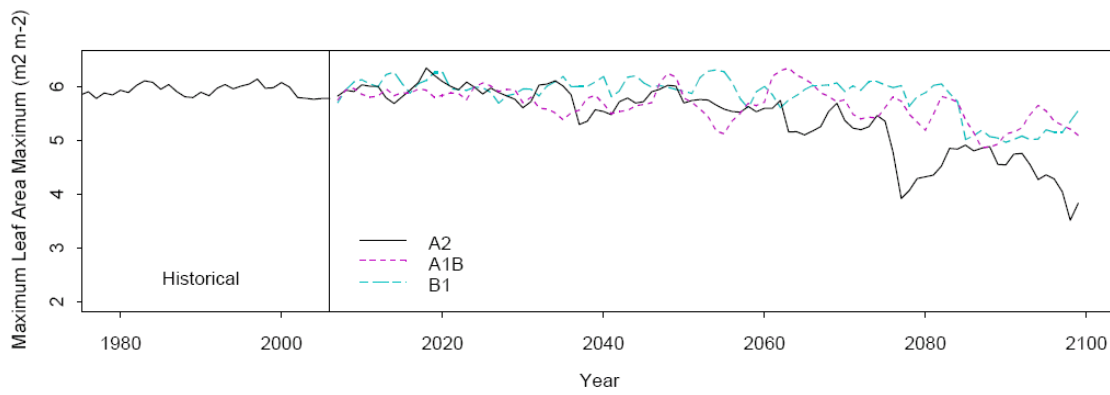


Figure 16. Leaf area index (m2 m-2) simulated by the dynamic global vegetation model MC1 under 3 different climate and CO₂ emission scenarios at Yosemite National Park.

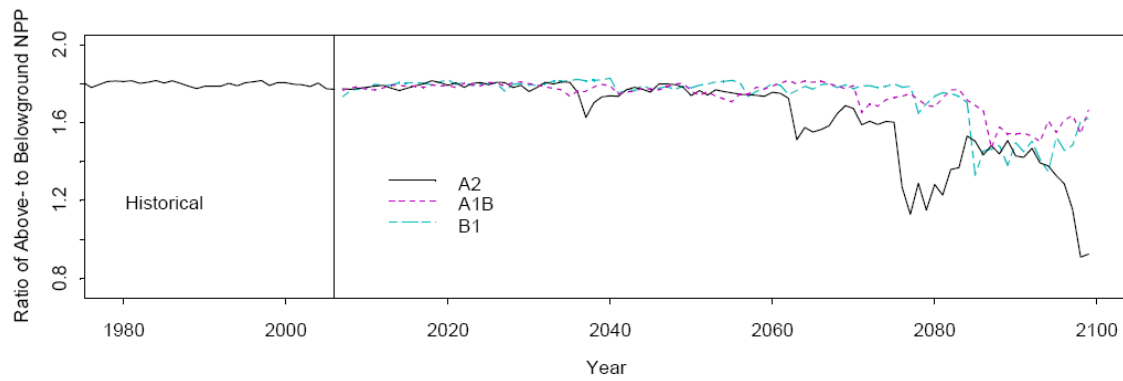


Figure 17. Ratio of aboveground to belowground net primary production simulated by the dynamic global vegetation model MC1 under 3 different climate and CO₂ emission scenarios for Yosemite National Park.

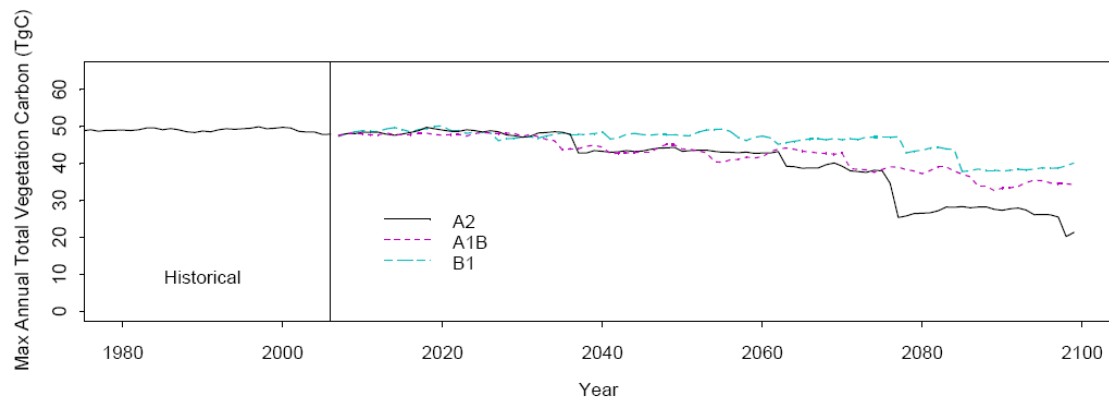


Figure 18. Total annual live vegetation carbon under 3 different climate and CO₂ emission scenarios simulated by the dynamic global vegetation model MC1 for Yosemite National Park.

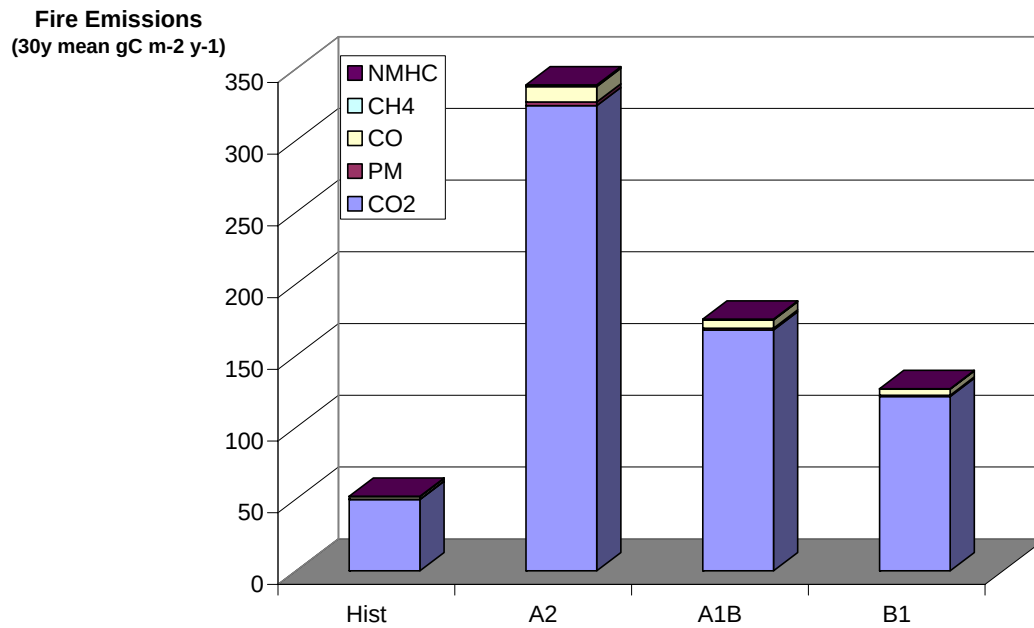


Figure 19. Carbon emissions from wildland fires simulated by the dynamic global vegetation model MC1 under 3 different climate and CO₂ emission scenarios over the last 30 years of the 20th century (Hist) and 21st century (remaining 3 bars) at Yosemite National Park.

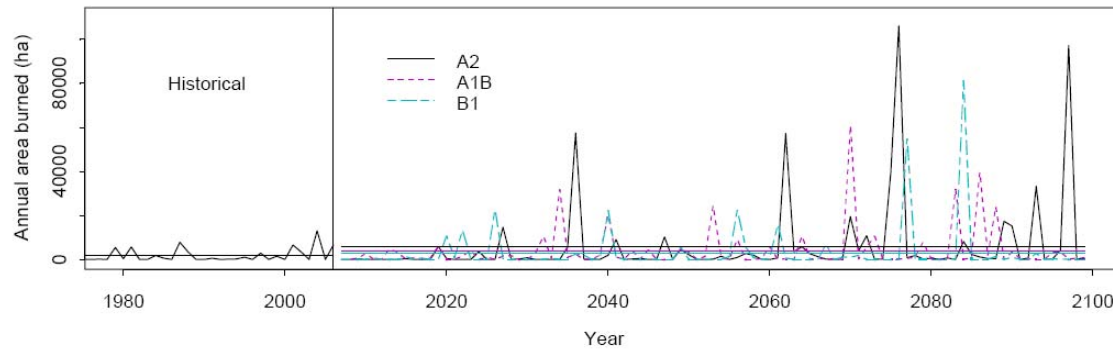


Figure 20. Area burned by wildland fire under 3 different climate and CO₂ emission scenarios as simulated by the dynamic global vegetation model MC1 for Yosemite National Park. Horizontal lines are averages over the last 30 years of the century of each of the scenarios, indicated by color.

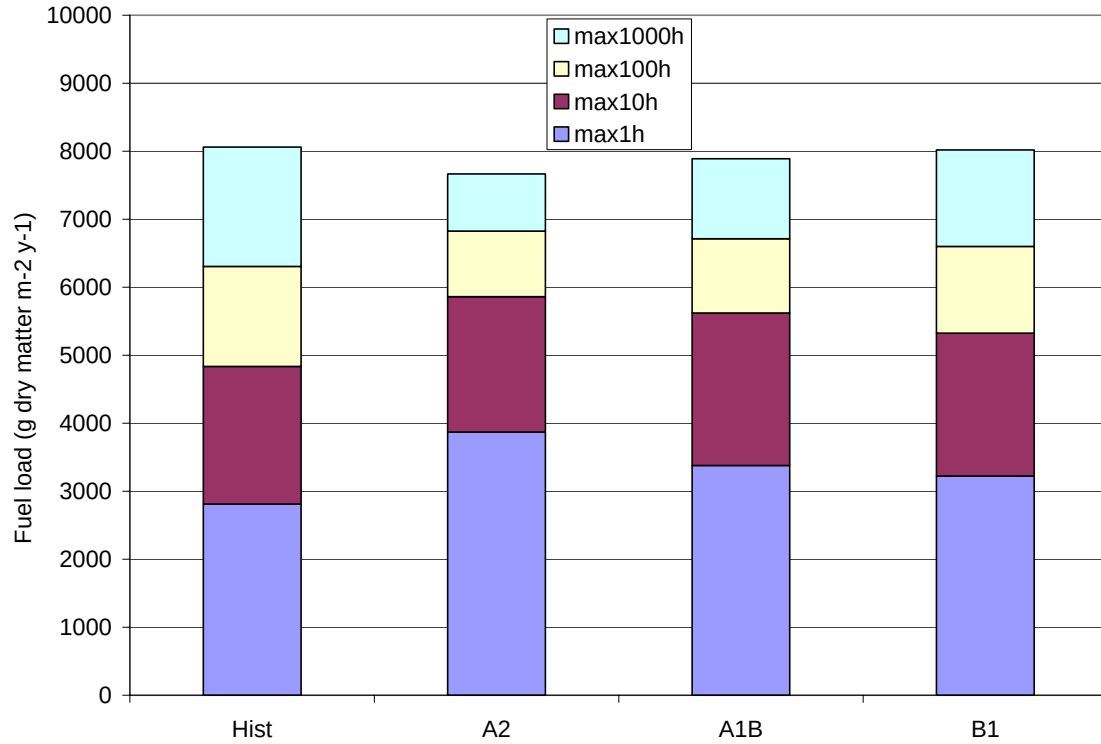
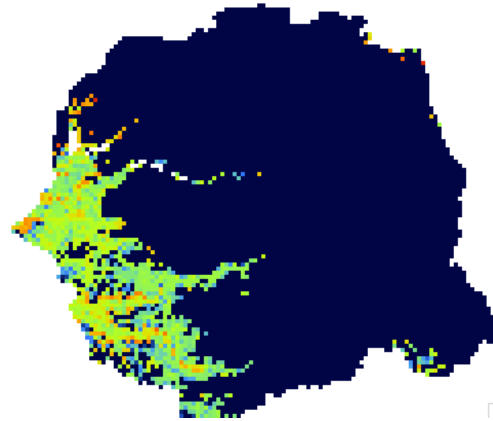


Figure 21. Fuel loads simulated by the dynamic global vegetation model MC1 for the last 3 decades of historical period and of the 21st century under 3 different climate and CO₂ emission scenarios at Yosemite National Park.

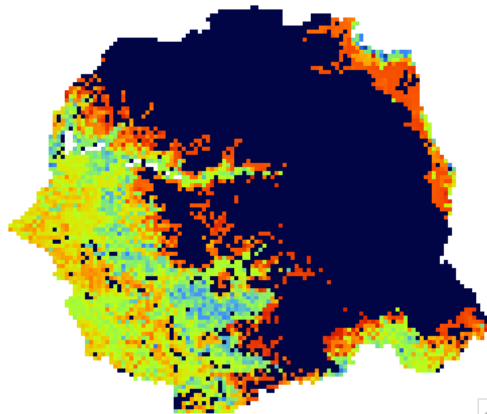
1971-2000



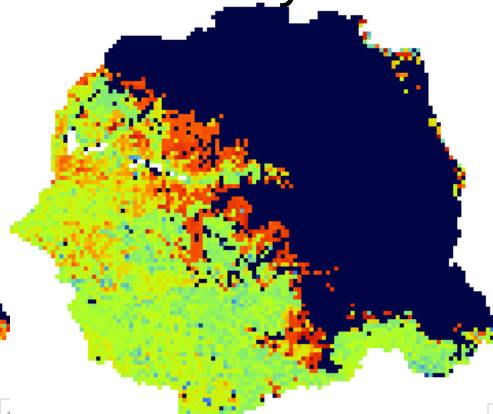
2071-2099



CSIRO B1



Hadley A1B



MIROC A2

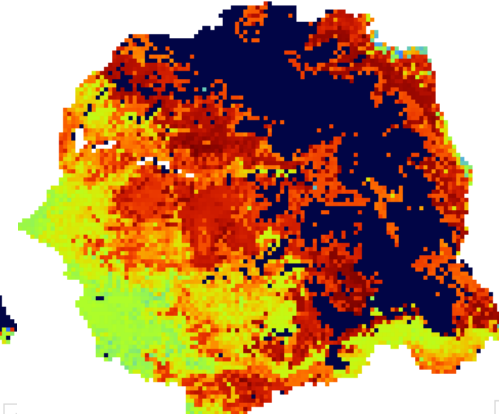


Figure 20. Ratio of biomass consumed by fire to NPP (“fire index”, TgC/TgC) under historical conditions and under 3 future CO_2 emission and climate scenarios, over the last 30 years of the 20th century and the 21st century as simulated by the dynamic global vegetation model MC1 for Yosemite National Park.

Appendix 1

Crosswalk between Yosemite's 1997 vegetation map, MC1 vegetation types (NB vtype¹) and California wildlife habitat relationship types (CWHR type²).

Yosemite's 1997 Vegetation	NB vtype¹	CWHR type²
Alpine talus slope	15	BAR
Alpine scree slope	15	BAR
Alpine Snow Patch Communities	15	BAR
Mesic rock outcrop	15	BAR
Boulder field	15	BAR
Conifer reproduction	VARIOUS ³	VARIOUS
Conifer plantation	5	SMC
Sparsely vegetated undifferentiated	15	BAR
Sparsely vegetated riverine flat	15	BAR
Non-alpine talus	15	BAR
Sparsely vegetated to non-vegetated exposed rock	15	BAR
Dome	15	BAR
Fissured rock outcrop	15	BAR
Sparsely vegetated rocky streambed	15	BAR
Snowfield/Glacier	16	GLA
Water	16	LAC
Permanently flooded, emergent, or floating vegetation	16	FEW
Urban/Developed	17	URB
Canyon live oak forest	6	MHW
Canyon live oak/manzanita forest	6	MHW
Canyon live oak/ponderosa pine/incense cedar forest	5	MHC
Canyon live oak/California laurel forest	6	MHW
Canyon live oak/foothill pine forest	5	MHC
Canyon live oak/manzanita forest	6	MHW
Interior live oak/canyon live oak woodland	6	MHW
Canyon live oak/buckeye woodland	6	MHW
Blue oak woodland	9	BOW
Interior live oak woodland	6	MHW
Quaking aspen forest	4	ASP
Quaking aspen/false hellbore forest	4	ASP
Quaking aspen/willow forest	4	ASP
Quaking aspen/willow talus slope	4	ASP
Quaking aspen/Jeffrey pine forest	4	ASP
Quaking aspen/big sagebrush forest	4	ASP
California black oak forest	6	MHW
California black oak/manzanita forest	6	MHW
California black oak/incense cedar forest	5	MHC
California black oak/bracken fern forest	6	MHW
Valley oak woodland	9	VOW
Black cottonwood forest	6	MRI
Black cottonwood/quaking aspen/Jeffrey pine forest	6	MRI
Mountain alder forest	6	MRI
Willow forest	6	MRI
White alder/bigleaf maple forest	6	MRI

Lodgepole pine/quaking aspen/Jeffrey pine forest	2	LPN
Lodgepole pine/quaking aspen forest	2	LPN
Lodgepole pine forest	2	LPN
Lodgepole pine/bog blueberry forest	2	LPN
Lodgepole pine woodland	2	LPN
Lodgepole pine/big sagebrush forest	2	LPN
Lodgepole pine/whitebark pine forest	2	LPN
Lodgepole pine/big sagebrush/Kentucky bluegrass forest	2	LPN
Lodgepole pine mesic forest	2	LPN
Lodgepole pine xeric forest	2	LPN
Ponderosa pine woodland	5	PPN
Ponderosa pine/black oak/manzanita woodland	5	PPN
Ponderosa pine/incense cedar forest	5	SMC
Ponderosa pine/incense cedar/black oak/canyon live oak forest	5	MHC
Jeffrey pine woodland	7	JPN
Jeffrey pine/manzanita woodland	7	JPN
Jeffrey pine/ceanothus woodland	7	JPN
Jeffrey pine/huckleberry oak woodland	7	JPN
Jeffrey pine/antelope bitterbrush woodland	7	JPN
Jeffrey pine/pinyon pine woodland	7	JPN
Jeffrey pine/mountain mahogany woodland	7	JPN
Jeffrey pine/white fir woodland	7	JPN
Jeffrey pine/canyon live oak/manzanita woodland	7	JPN
Jeffrey pine/red fir woodland	7	JPN
Foothill pine woodland	9	BOP
Foothill pine/interior live oak/manzanita woodland	5	MHC
Knobcone pine/manzanita woodland	8	CPC
Knobcone pine/canyon live oak woodland	8	CPC
Knobcone pine/chamise woodland	8	CPC
Pinon pine woodland	7	EPN
Pinon pine/mountain mahogany/sagebrush woodland	7	EPN
Pinon pine/gooseberry/sagebrush woodland	7	EPN
Western white pine/needlegrass woodland	7	JPN
Whitebark pine woodland	2	SCN
Whitebark pine/sedge woodland	2	SCN
Whitebark pine/mountain hemlock woodland	2	SCN
Whitebark pine/lodgepole pine/mountain hemlock krummholz forest	1	ADS
Limber pine woodland	2	SCN
Douglas fir/canyon live oak forest	5	DFR
Douglas fir/white alder forest	5	DFR
Giant sequoia forest	5	SMC
Giant sequoia/sugar pine/dogwood forest	5	SMC
Mountain hemlock/western white pine/lodgepole pine forest	2	SCN
Ref fir/lodgepole pine forest	4	RFR
Red fir/western white pine forest	4	RFR
Red fir/white fir forest	4	RFR
White fir forest	5	WFR
Sierra juniper woodland	7	JUN

Sierra juniper/oceansprary woodland	7	JUN
Sierra juniper/mountain mahogany/sagebrush woodland	7	JUN
Incense cedar/white alder forest	5	MHC
Western white pine/red fir/lodgepole pine forest	4	RFR
White fir/red fir/sugar pine/Jeffrey pine forest	5	WFR
White fir/sugar pine/incense cedar/Jeffrey pine forest	5	WFR
Douglas fir/white fir/incense cedar/ponderosa pine forest	5	DFR
Chamise	11	CRC
Interior live oak/buckeye	6	MHW
Whitethorn chaparral	11	MCP
Whitethorn ceanothus	11	MCP
Tobacco brush	11	MCP
Mountain misery	11	MCP
Big sagebrush	10	SGB
Low sagebrush	10	LSG
Mountain mahogany woodland	11	MCP
Antelope bitterbrush	11	MCP
Silver lupine/brome	11	MCP
Big sagebrush/silver sagebrush	10	SGB
Mountain big sagebrush/timberline sagebrush/oceanspray	10	SGB
Chamise/buckbrush/manzanita	11	CRC
Manzanita/chinquapin/huckleberry oak	11	MCP
Mountain mahogany/buckbrush/manzanita	11	MCP
Deerbrush	11	MCP
Deerbrush/manzanita	11	MCH
Oregon white oak	11	MCP
Sierra willow/swamp onion	11	MCH
Willow/meadow shrubland	6	MRI
Willow riparian shrubland	6	MRI
Willow talus shrubland	11	MCH
Mesic montane shrubland	11	MCP
Shorthair sedge herbaceous	18	WTM
California annual grassland	13	AGS
Upland herbaceous	13	PGS
Post-clearcut shrub/herbaceous	13	PGS
Mesic post-fire herbaceous	13	PGS
Intermittantly to seasonally flooded meadow (above 5500 feet)	18	WTM
Intermittantly to seasonally flooded meadow (below 5500 feet)	13	PGS
Semi-permanently to permanently flooded meadow (above 5500 feet)	18	WTM
Semi-permanently to permanently flooded meadow (below 5500 feet)	13	PGS

1. NB vtype classifications used by MC1:

1. Alpine
2. Subalpine Forest
3. Coastal Conifer Forest
4. Montane Conifer Forest

5. Mixed Evergreen Forest (aka Mixed Conifer and Hardwood Forest, or simply Mixed Forest)
6. Hardwood Forest
7. Conifer Woodland
8. Mixed Evergreen Woodland (aka Mixed Conifer and Hardwood Woodland, or simply Mixed Woodland)
9. Hardwood Woodland
10. Sagebrush
11. Montane Chaparral
12. Coastal Chaparral
13. Grassland
14. Desert
15. Natural Barren
16. Water
17. Developed
18. Subalpine Meadow

2. The California Wildlife Habitat Relationships system (CWHR) classifies existing vegetation types important to wildlife and was developed to categorize major vegetative complexes at a scale sufficient to predict wildlife-habitat relationships in California. The following link describes the CWHR in detail: <http://www.dfg.ca.gov/biogeodata/cwhr/>

3. Conifer reproduction was assigned to potential vegetation type based on surrounding vegetation