View of Sequoia National Park, California (photo P. Gonzalez)

Climate Change Trends and Vulnerability to Biome Shifts in the Southern Sierra Nevada

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Introduction

Emissions from vehicles, power plants, deforestation, and other human activities have increased atmospheric concentrations of greenhouse gases, causing an increase of global average surface temperature of 0.7 ± 0.2°C from 1906 to 2005 (IPCC 2007a) and other climate changes. Field measurements from around the world show that climate change is altering ecosystems (IPCC 2007b) by causing the extinction of some animal species (Pounds et al. 2006), shifting biomes (major vegetation formations; Gonzalez et al. 2010), and causing other fundamental ecological changes (Rosenzweig et al. 2008).

Climate change has altered wildfire frequency and extent in the 20th century. Multivariate analysis of wildfire across the western U.S. from 1916 to 2003 indicates that climate was the dominant factor controlling burned area, even during periods of human fire suppression (Littell et al. 2009). In mid-elevation conifer forests of the western U.S., increases in spring and summer temperatures, earlier snowmelt, and longer summers increased fire frequency 400% and burned area 650% from 1970 to 2003 (Westerling et al. 2006). Reconstruction of fires of the past 400 to 3000 years in the western U.S. (Marlon et al. 2012, Trouet et al. 2010) and in Yosemite and Sequoia National Parks, California (Swetnam 1993, Swetnam et al. 2009, Taylor and Scholl 2012) confirm that temperature and drought are the dominant factors explaining fire occurrence.

Recognizing the interconnections between climate change and wildfire, the National Park Service, USDA Forest Service, and other agencies formed the Southern Sierra Conservation Cooperative in 2009 to collaboratively support research that would inform fire and other resource management under climate change. Sequoia and Kings Canyon National Parks started an applied research project "Alternative Fire Management Futures" in 2010 to provide the scientific information needed for the adaptation of fire management to climate change.

This report supports that effort by presenting results aimed at two objectives:

1. To spatially analyze historical and projected climate changes,
2. To spatially analyze historical vegetation shifts and future vulnerability of ecosystems to biome shifts.

The report presents results for three analysis areas: the Southern Sierra Conservation Cooperative (a protected-area centered ecosystem [PACE]), Sequoia and Kings Canyon National Parks, and Sequoia National Forest, all in California, USA. These results provide background information to supplement fire modeling conducted by colleagues on the southern Sierra Nevada project.

Historical Climate Trends

From 1901 to 2002, mean annual temperature increased across most of California (Figure 1; Mitchell and Jones 2005, Gonzalez et al. 2010), but showed no statistically significant change in the three southern Sierra analysis areas (Figure 2, Table 1). From 1941 to 2008, however, mean annual temperature at the Grant Grove, California weather station in Kings Canyon National Park, shows a statistically significant increase (Figure 2, Table 1; data from the National Oceanic and Atmospheric Administration).

Analyses of 1950-1999 temperature measurements from weather stations across the western U.S., including the southern Sierra, detected statistically significant annual and winter warming, while analyses of causal factors attributed the warming to human-caused climate change (Barnett et al. 2008, Bonfils et al. 2008). Analyses of 1950-2005 western U.S. weather station data also detected a shift of 1.5 days decade^{-1} of spring warmth to earlier in the year and found that only one-third of the shift was attributable to natural variability (Ault et al. 2011).

Since 1950, the frequency of extreme temperatures and the length of the growing season have increased for the southwestern U.S. as a whole (Kunkel et al. in review). For the southwestern U.S., the number of four-day periods of one-in-five year hot temperatures (or 80% extreme) increased approximately 90% (Kunkel et al. in review).

From 1901 to 2002, total annual precipitation increased across California (Figure 3; Mitchell and Jones 2005, Gonzalez et al. 2010), but showed no statistically significant change in the three southern Sierra analysis areas (Figure 4, Table 1). From 1941 to 2010, total annual precipitation at the Grant Grove, weather station decreased, but the trend was statistically significant (Figure 4, Table 1; data from the National Oceanic and Atmospheric Administration).

Measurements from weather stations and snow courses across the western U.S, including the southern Sierra Nevada, have detected changes in numerous precipitation variables the last half of the 20th century and attribution of these to human-caused climate change, including decreased snowpack (Barnett et al. 2008; Pierce et al. 2008), decreased ratio of snow to rain (Pierce et al. 2008), and earlier spring streamflow (Barnett et al. 2008).

Historical Vegetation Shifts

Climate change is shifting vegetation latitudinally and elevationally at sites in boreal, temperate and tropical ecosystems (IPCC 2007, Rosenzweig et al. 2008, Gonzalez et al. 2010). Changes in climate alter plant mortality and recruitment by exceeding physiological thresholds and changing wildfire and other disturbances. The resulting replacement of dominant plant

species can entirely change the biome of an area. Biomes are major vegetation formations characterized by the same life form, such as temperate broadleaf forest or temperate grassland (Woodward et al. 2004). Field research has detected elevational and latitudinal shifts of biomes around the world attributable to climate change (Gonzalez et al. 2010).

A few research efforts have observed shifts of individual tree species in the Sierra Nevada connected to climate conditions, but not necessarily to human-caused climate change. At sites in Sequoia and Yosemite National Parks, lodgepole pine (*Pinus contorta*), shifted 500 m since the last glacial retreat ~4700 BC (Anderson 1996). In the central Sierra Nevada, ponderosa pine (*Pinus ponderosa*) possibly showed upslope shifts between 1945 and 1992 (Thorne et al. 2008). At sites in the California Coastal Range, Cascades, and Sierra Nevada, spatial analyses of climate and plant species occurrences seem to show a downslope shift of ~90 m of the mean optimal elevation of 72% of 64 species from the 1930s to 2000s, tracking an increase in climatic water balance (Crimmins et al. 2011). Stephenson and Das (2011), however, have called into question their methods and conclusions.

Analyses of field measurements in the Inyo and Humbolt-Toiyabe National Forests and Yosemite National Park have produced the only detection of a biome shift in the southern Sierra Nevada attributable to human-caused climate change, In this case, pine forest has encroached into alpine meadows and snowfields between 1880 and 2002, correlated with increase in minimum temperatures (Millar et al. 2004).

Spatial analysis of the only repeat land cover spatial data for the U.S., the National Land Cover Database (NLCD) derived by the U.S. Geological Survey from Landsat satellite data (Fry et al. 2011), showed a change in vegetation type of <1% of the land area of the three southern Sierra areas from 2001 to 2006 (Table 2, Figures 5, 6). Evergreen forest to shrubland comprised the greatest change. Many factors, including urbanization, fire, or climate, could have contributed to the changes.

Growing forests naturally remove carbon dioxide, the main greenhouse gas, from the atmosphere and reduce the magnitude of global climate change. When climate change shifts vegetation, it also shifts the distribution of carbon, potentially changing the mass of carbon per unit area (carbon density) depending on the carbon densities of the shifting vegetation types. Groves of giant sequoia (*Sequoiadendron giganteum*) in the southern Sierra Nevada contain carbon at densities of up to 2700 t ha^{-1} (Table 3), nearly the highest in the world (Aalde et al. 2006). Coast redwood (*Sequoia sempervirens*) contains the carbon at the highest density in the world, 2900 t ha^{-1} (Busing and Fujimori 2005). Average forest carbon density in the southern

Sierra is 200 ± 120 t ha^{-1} (Figure 7, Table 3; Blackard et al. 2008), higher than average Amazon rainforest carbon densities (Baker et al. 2004).

Future Climate Projections

The Intergovernmental Panel on Climate Change (IPCC) has coordinated research groups to project possible future climates under defined greenhouse gas emissions scenarios (IPCC 2007a). The three main IPCC greenhouse gas emissions scenarios are B1 (lower emissions), A1B (medium emissions), and A2 (higher emissions). Actual global emissions are on a path above IPCC emissions scenario A2 (Friedlingstein et al. 2010).

For the three main IPCC emissions scenarios, temperature could increase at rates of 2.6 ± 0.9 ^{o}C century[-1] to 4.0 ± 1.0ºC century[-1] between the periods 1961-1990 and 2071-2000 (Table 1; Gonzalez et al. 2010). This analysis used projections downscaled to 50 km spatial resolution for three general circulation models (GCMs) that bracket the range of all 23 GCMs (Table 1; Gonzalez et al. 2010). Spatial analyses using projections downscaled to 4 km spatial resolution for all 18 GCMs available for IPCC emissions scenario A2 were consistent with the results at 50 km spatial resolution (data from Conservation International <http://futureclimates.conservation.org> using method of Tabor and Williams (2010)).

In addition, analyses at 4 km spatial resolution characterize the spatial variation and the uncertainty of the projections. Projected temperature changes increase with distance from the ocean (Figure 8). The temperature projections of the 18 GCMs are generally in close agreement, with a coefficient of variation (the standard deviation as a fraction of the mean) of 0.23 for the southern Sierra, indicating that the temperature uncertainty is equivalent to approximately one-fourth of the average value (Figure 9).

Other fire and vegetation modeling in the "Alternative Fire Management Futures" project uses output from the two GCMs that the State of California has used for climate change impacts analyses – GFDL 2.1 and PCM (Cayan et al. 2008). GFDL 2.1 projects temperatures that are ~10% warmer than the average of the 18 GCM ensemble (Figure 10), while PCM projects temperatures that are the least warm in the ensemble (Figure 11).

The averages of the 18 GCMs show projected decreases in total annual precipitation under the three emissions scenarios for the three southern Sierra areas (Figure 12, Table 1). The GCMs show low agreement, however, with half projecting increases in precipitation and half projecting decreases for the central part of the southern Sierra, with one GCM flipping from increase to decrease for parts of Kings Canyon, Sequoia, and Yosemite National Parks (Figure

13). The coefficient of variation of the precipitation projections is 56 for the southern Sierra, indicating that the precipitation uncertainty is over fifty times the average value.

GFDL 2.1 projects the greatest decreases in total annual precipitation of the 18 GCM ensemble for most of the southern Sierra (Figure 14). PCM projects precipitation decreases ~17% less than the 18 GCM ensemble (Figure 15).

Taken together, the temperature and precipitation projections of the 18 GCMs form a cloud of potential future climates (Figures 16-18). For all three areas, the GCMs show nearly complete disagreement in their precipitation projections. Furthermore, GFDL 2.1 and PCM do not bracket the range of projected climates for the southern Sierra Nevada.

GCMs project potential increases in the frequency of extreme temperature and precipitation events (IPCC 2012). Across western North America, one-in-twenty year hot temperatures (or 95% extreme) may increase in frequency to once every year or once in two years (IPCC 2012). At the Grant Grove weather station, the one-in-twenty year average annual maximum temperature for the period 1983-2009 was 15.5ºC (60ºF.) (data from the National Oceanic and Atmospheric Administration, the period spans more than twenty years due to incomplete measurement years). One-in-twenty year storms may increase in frequency to one in 8 to 10 years (IPCC 2012). Northern California may experience a 25 to 200% increase in one-in-100 year rainstorms (99% extreme) (Cayan et al. 2008). In the southern Sierra area, modeling under emissions scenario A2 projects 5-10 more consecutive days per year with maximum temperatures > 35ºC and 10-15 more consecutive days per year with rainfall < 3 mm per day (Kunkel et al. in review).

Projected Future Vulnerability to Biome Shifts

Modeling of potential future vegetation under climate change used output from the MC1 dynamic global vegetation model (DGVM; Daly et al. 2000) and methods previously used in a global analysis of vulnerability to biome shifts (Gonzalez et al. 2010). MC1 uses five climate variables (monthly mean, maximum and minimum temperature; precipitation; vapor pressure) and five soil variables (soil depth; bulk density; clay, sand and rock fractions) to run interacting modules of biogeography, biogeochemistry and wildfire.

The biogeography module identifies the potential vegetation type of a pixel by modeling plant life-form as distinguished by leaf characteristics. The relative proportion of different woody life-forms is determined at each annual time step by position along gradients of minimum temperature and growing season precipitation. The minimum temperature gradient runs from

evergreen needle-leaf dominance (-15 °C) through deciduous broadleaf dominance to broadleaf evergreen dominance (18 °C). The relative proportion of C3 and C4 grasses is determined by estimating potential productivity as a function of soil temperature during the three warmest consecutive months.

The biogeochemistry module calculates the biomass of trees and grasses for each pixel by modeling net primary productivity (NPP), organic matter decomposition and carbon, nitrogen and water cycling. MC1 simulates changes to plant physiology, nutrient cycling, water use and biomass due to changes in atmospheric CO_2.

The wildfire module simulates wildfire occurrence and behavior based on fuel loadings and fuel and soil moisture and calculates resulting changes in plant life-form mixtures and biomass. The modeled plant life-form mixture from the biogeography module together with woody plant and grass biomass from the biogeochemistry module determine the vegetation type that occurs at each pixel each year. The 34 MC1 potential vegetation types (Kuchler 1964, VEMAP Members 1995) were combined into 13 biomes (FAO 2001, Woodward et al. 2004). For each pixel, the biome that MC1 modeled for the majority of years during each of two periods (1961–90, 2071–2100) represents the average vegetation for each period.

The climate inputs for MC1 came from an ensemble of three GCMs aimed at representing lower (CSIROMk3), medium (HadCM3) and higher (MIROC 3.2 medres) temperature sensitivity for the period 2000–2100 (IPCC 2007a). GCM runs for the three emissions scenarios used in the IPCC Fourth Assessment Report (AR4; IPCC 2007a, 2007b) represent lower (B1), medium (A1B), and higher (A2) greenhouse gas emissions. The nine GCM–emission scenario combinations bracket a substantial part of the range of temperature projections of the 59 AR4 combinations.

Limitations of the methods include limited accuracy of the MC1 DGVM, use of only one DGVM, and inaccuracies in how GCMs simulate climate. In addition, use of the biome as a unit of analysis may understate vulnerability because the broad definition of a biome allows for changes in species composition without conversion to a different biome. DGVMs delineate potential, not realized, vegetation distributions. Survival and dispersal capabilities of species, human barriers to dispersal, interspecific competition, evolutionary adaptation, changing pests and pathogens and other factors will lead to biome changes occurring at varying rates. In some cases, rates of climate change may exceed the dispersal abilities of individual species. Conditions projected for 2100 AD may reflect committed changes, but long time-scales of atmospheric equilibrium and ecological processes create a double transient situation.

MC1 output under the standard 1961-1990 climatology shows the existing elevation gradient of vegetation from the Central Valley to the crest of the Sierra Nevada (Figure 19). Using the strictest criterion of complete agreement of all nine GCM–emission scenario combinations, MC1 output for the period 2071-2100 shows potential upslope shifting across one-fifth of the southern Sierra (Figure 20, Table 2).

Complete agreement of all nine GCM–emission scenario combinations indicates high vulnerability of ecosystems to biome change. One-fifth of the southern Sierra, Sequoia and Kings Canyon National Parks, and Sequoia National Park are areas of high vulnerability (Table 2). For the entire southern Sierra area, temperate broadleaf forest shows the highest losses as oaks shift and mix may with conifers, creating temperate mixed forest areas. In Sequoia and Kings Canyon National Parks, subalpine forest shows the highest potential losses as temperate conifers such as pines shift up and dominate fir and other subalpine conifers.

Using a worst-case criterion of any GCM–emission scenario combination showing a biome change, MC1 output for the period 2071-2100 shows extensive vegetation shifts covering half of the southern Sierra and four-fifths of Sequoia and Kings Canyon National Parks (Figure 21). Conversely, areas in which no GCM projects a change in biome comprise areas of low vulnerability and potential refugia. These areas cover half of the southern Sierra and one-fifth of Sequoia and Kings Canyon National Parks (Table 2). The fraction of GCM–emission scenario combinations that disagree is a measure of the uncertainty of the projections. Conversely, the fraction of GCM–emission scenario combinations that agree is a measure of confidence in the projections (Figure 22). Average confidence was 0.37 ± 0.41 in the southern Sierra and 0.62 ± 0.37 in Sequoia and Kings Canyon National Parks (Table 2).

Conclusions

1. Historical climate changes in the three southern Sierra areas are not statistically significant for the period 1901-2002, but are statistically significant for the period 1950-1999.
2. A historical biome shift has occurred at sites in Yosemite National Park.
3. Projected warming shows agreement across general circulation models (GCMs).
4. GCMs disagree on the direction of projected precipitation changes in the southern Sierra.
5. PCM temperature projections are the least warm of all GCMs for scenario A2.
6. GFDL 2.1 precipitation projections are the lowest of all GCMs for scenario A2.
7. A substantial area is vulnerable to vegetation shifts at the biome level.
8. National park areas show higher vulnerability to biome shifts.

Table 1. Historical and projected climate (mean ± standard deviation (SD)) trends for the southern Sierra Nevada (Mitchell and Jones 2005, IPCC 2007a, Gonzalez et al. 2010). Historical trends also given for the Grant Grove, California weather station (data from the National Oceanic and Atmospheric Administration). Climate projections for the IPCC emissions are calculated at 50 km spatial resolution (Gonzalez et al. 2010) and, for emissions scenario A2, also at 4 km spatial resolution (data from Conservation International using method of Tabor and Williams (2010)). Note "century^{-1}" is the fractional change per century, so that -0.19 century^{-1} is a decrease of 19% in a century.

	Southern Sierra Conservation Cooperative		Sequoia and Kings Canyon National Parks		Sequoia National Forest		Grant Grove weather station		
	mean	SD	mean	SD	mean	SD	mean	SD	units
Historical Climate			1901-2002				1941-2008 (t) 1941-2010 (p)		
temperature annual average	10.3	0.5	9.2	0.6	12.0	0.6	8.0	0.6	ºC
temperature linear trend	0.1	1.8	0.2	2.1	0.2	1.9	2.2	2.7	ºC century^{-1}
precipitation annual average	750	220	690	220	1100	500	1100	350	mm year^{-1}
precipitation linear trend	0.08	0.96	0.11	1.05	0.11	1.12	-0.19	1.68	century^{-1}
Projected Climate Changes by IPCC scenario			1990-2100						
B1 (lower emissions)									
temperature	2.6	0.9	2.7	1.0	2.6	0.7			ºC century^{-1}
precipitation	-0.11	0.21	-0.12	0.15	-0.14	0.10			century^{-1}
A1B (medium emissions)									
temperature	3.4	0.9	3.5	1.0	3.4	0.7			ºC century^{-1}
precipitation	-0.07	0.19	-0.08	0.10	-0.09	0.10			century^{-1}
A2 (higher emissions)									
temperature	3.9	0.9	4.0	1.0	3.9	0.9			ºC century^{-1}
precipitation	-0.04	0.19	-0.05	0.15	-0.06	0.15			century^{-1}

Table 2. Historical vegetation and projected biome changes (Historical data: National Land Cover Database (NLCD), derived by the U.S. Geological Survey from Landsat satellite data (Fry et al. 2011); Projections: MC1 Dynamic Global Vegetation Model Output from R. Neilson, J. Lenihan, R. Drapek; Analysis: P. Gonzalez, using methods in Gonzalez et al. (2010)).

	Southern Sierra Conservation Cooperative	Sequoia and Kings Canyon National Parks	Sequoia National Forest
Historical Vegetation Changes		2001-2006	
Fraction of area on which the vegetation type changed	0.006	0.002	0.004
Highest changes	Evergreen forest to shrub Grassland to mixed forest	Evergreen forest to shrub Shrub to barren	Evergreen forest to shrub Grassland to mixed forest
Projected Biome Changes		1990-2100	
Fraction of area in a vulnerability class High Vulnerability (All GCMs change)	0.20	0.23	0.22
Medium Vulnerability (Any GCM changes)	0.52	0.79	0.64
Potential Refugia (No GCM changes)	0.48	0.21	0.36
Confidence (mean ± SD)	0.37 ± 0.41	0.62 ± 0.37	0.40 ± 0.39
Highest projected losses	Temperate broadleaf forest Subalpine forest	Subalpine forest Shrubland	Shrubland Temperate grassland
Highest projected gains	Temperate mixed forest Subtropical Grassland	Subtropical grassland Temperate mixed forest	Subtropical grassland Temperate mixed forest

Table 3. Aboveground forest carbon densities (t ha^{-1}) in 2001, from forest inventories and MODIS satellite data (data Blackard et al. 2008, analysis P. Gonzalez).

	Southern Sierra Conservation Cooperative	Sequoia and Kings Canyon National Parks	Sequoia National Forest
mean	200	230	210
SD	120	180	150
minimum	4	30	40
maximum	2700	2700	2400

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Aboveground Forest Carbon Density
From field measurements and MODIS satellite data

Data: Blackard et al. 2008 Remote Sensing of Environment
Analysis: P. Gonzalez

Figure 8.

Figure 9.

Figure 10.

Figure 11.

Figure 12.

50 km

50% increase

no change

50% decrease

Projected Precipitation Change 2000-2100
Intergovernmental Panel on Climate Change Emissions Scenario A2, 18 General Circulation Models

Data: Downscaling of Mitchell and Jones 2005 by Hijmans et al. 2005, downscaling of IPCC 2007 CMIP3 by Conservation International using method of Tabor and Williams 2010. Analysis: P. Gonzalez.

Nevada

Yosemite National Park

California

Kings Canyon National Park

Sequoia National Park

Sequoia National Forest

Southern Sierra Conservation Cooperative

Figure 13.

Agreement of Projections of Annual Precipitation Change 2000-2100
Intergovernmental Panel on Climate Change Emissions Scenario A2, 18 General Circulation Models

Data: Downscaling of Mitchell and Jones 2005 by Hijmans et al. 2005, downscaling of IPCC 2007 CMIP3 by Conservation International using method of Tabor and Williams 2010. Analysis: P. Gonzalez.

Figure 14.

Figure 15.

Place of PCM in Projections of Annual Precipitation Change 2000-2100
Intergovernmental Panel on Climate Change Emissions Scenario A2, 18 General Circulation Models

Data: Downscaling of Mitchell and Jones 2005 by Hijmans et al. 2005, downscaling of IPCC 2007 CMIP3 by Conservation International using method of Tabor and Williams 2010. Analysis: P. Gonzalez.

Figure 16.

Figure 17.

Figure 18.
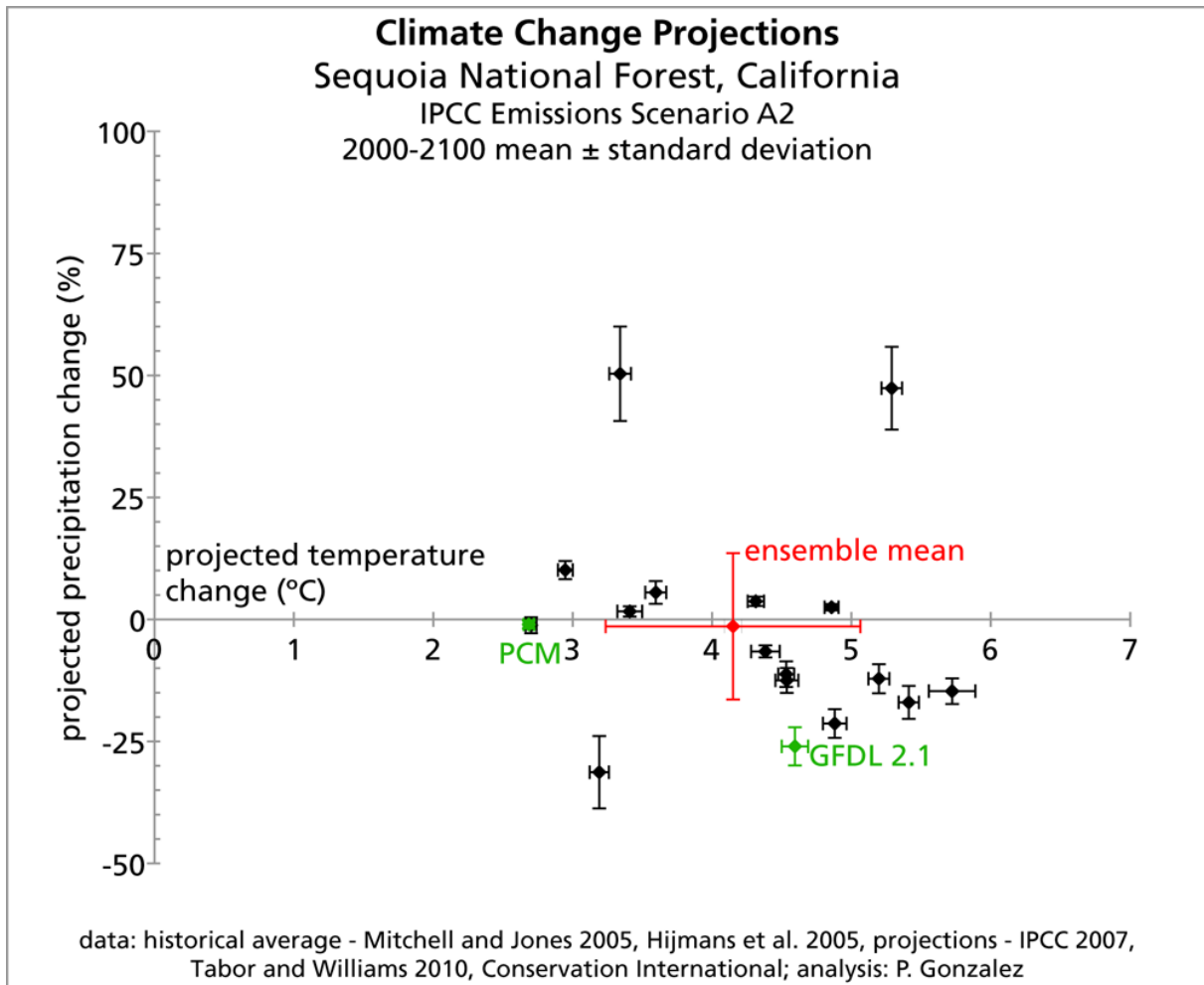
Figure 19.

Figure 20.

Figure 21.

Potential Vegetation, 2071-2100 Climate, Worst Case

MC1 Dynamic Global Vegetation Model
Any of Nine IPCC Emissions Scenario-General Circulation Model Combinations Projects Biome Change

Analysis of 8 km data using method of Gonzalez, Neilson, Lenihan, Drapek 2010. Global Ecology and Biogeography.

Figure 22.

Confidence in Projections of Potential Vegetation, 2071-2100
MC1 Dynamic Global Vegetation Model
Fractional Agreement of Nine IPCC Emissions Scenario-General Circulation Model Combinations

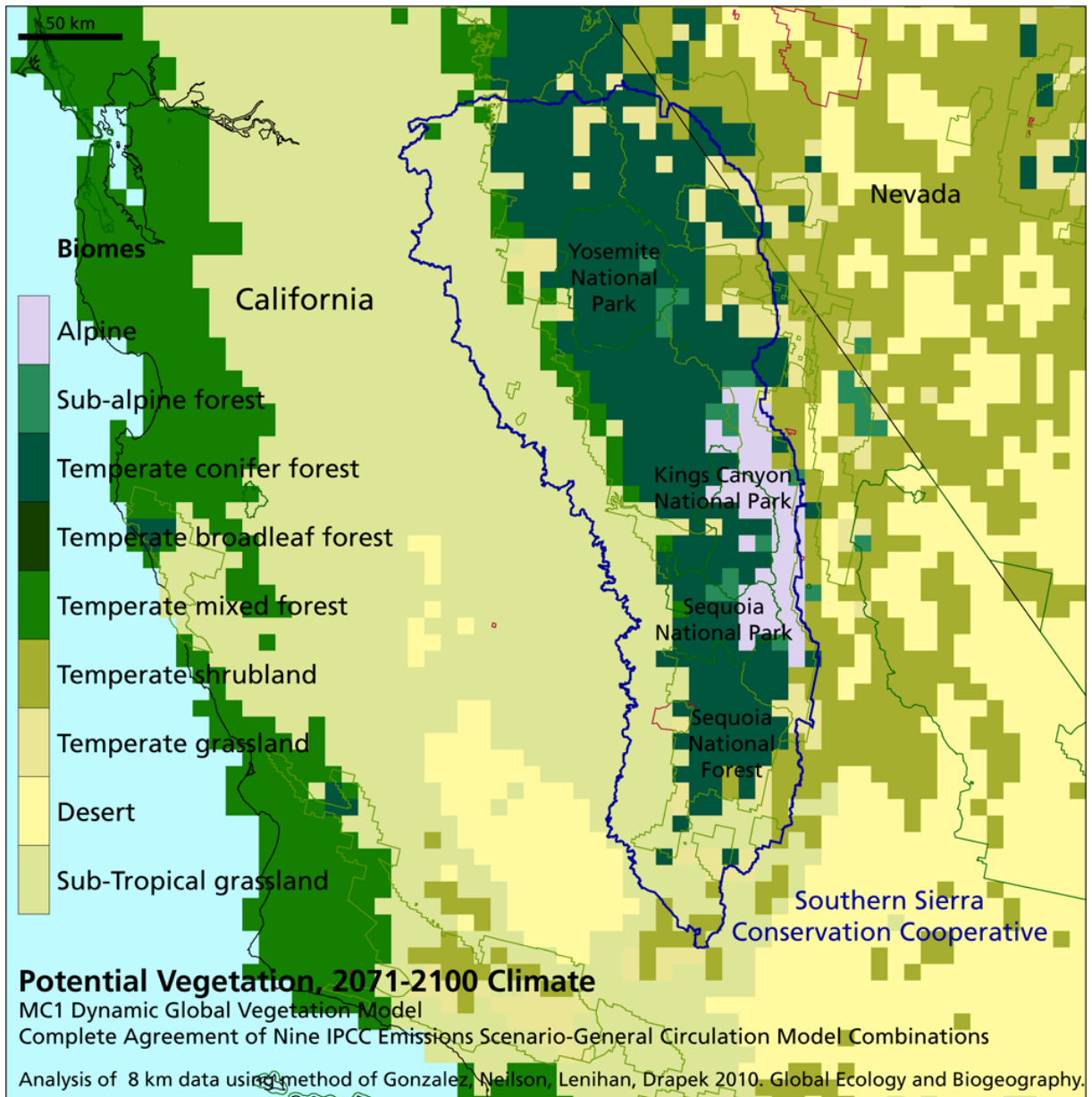Analysis of 8 km data using method of Gonzalez, Neilson, Lenihan, Drapek 2010. Global Ecology and Biogeography.
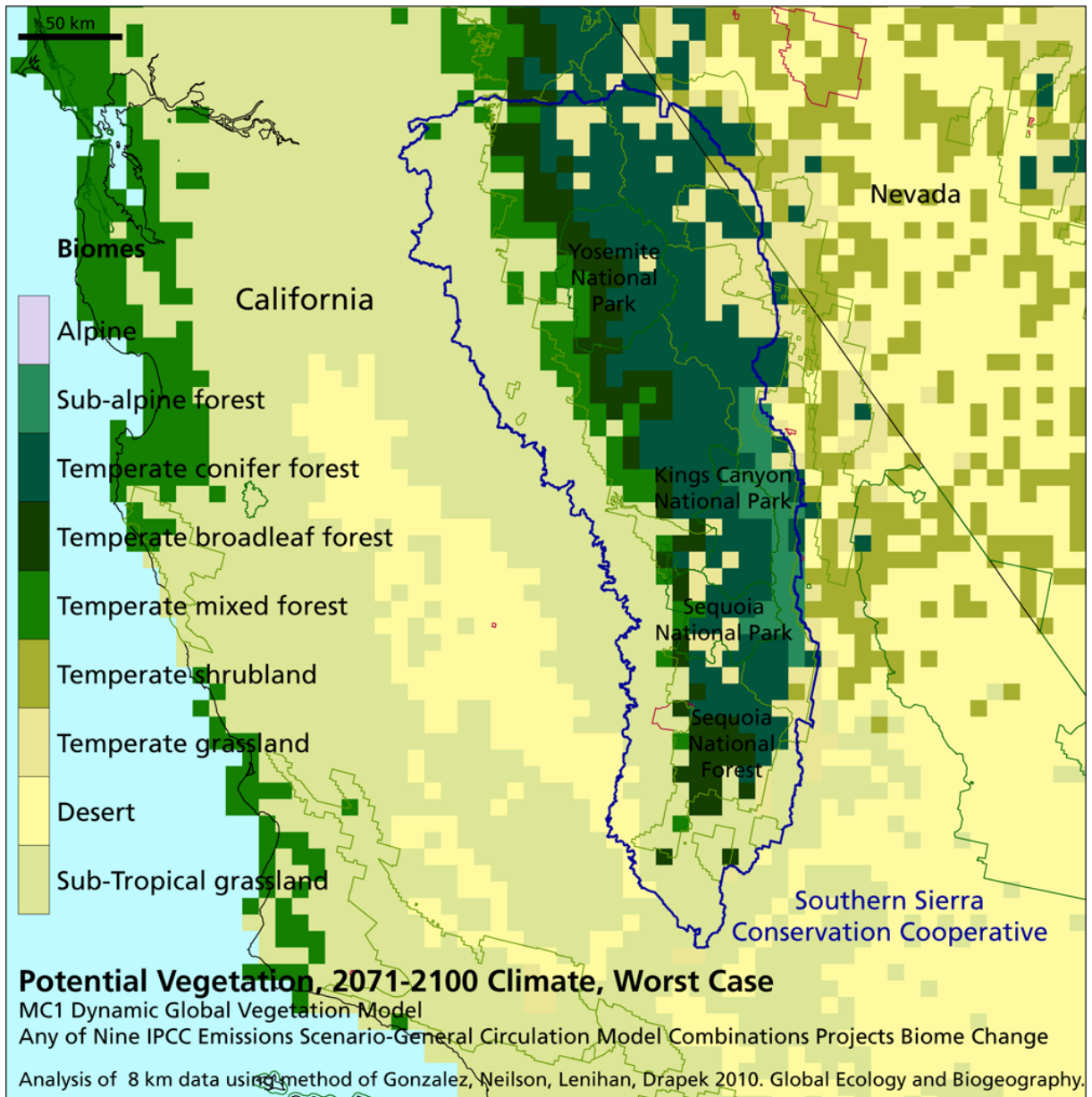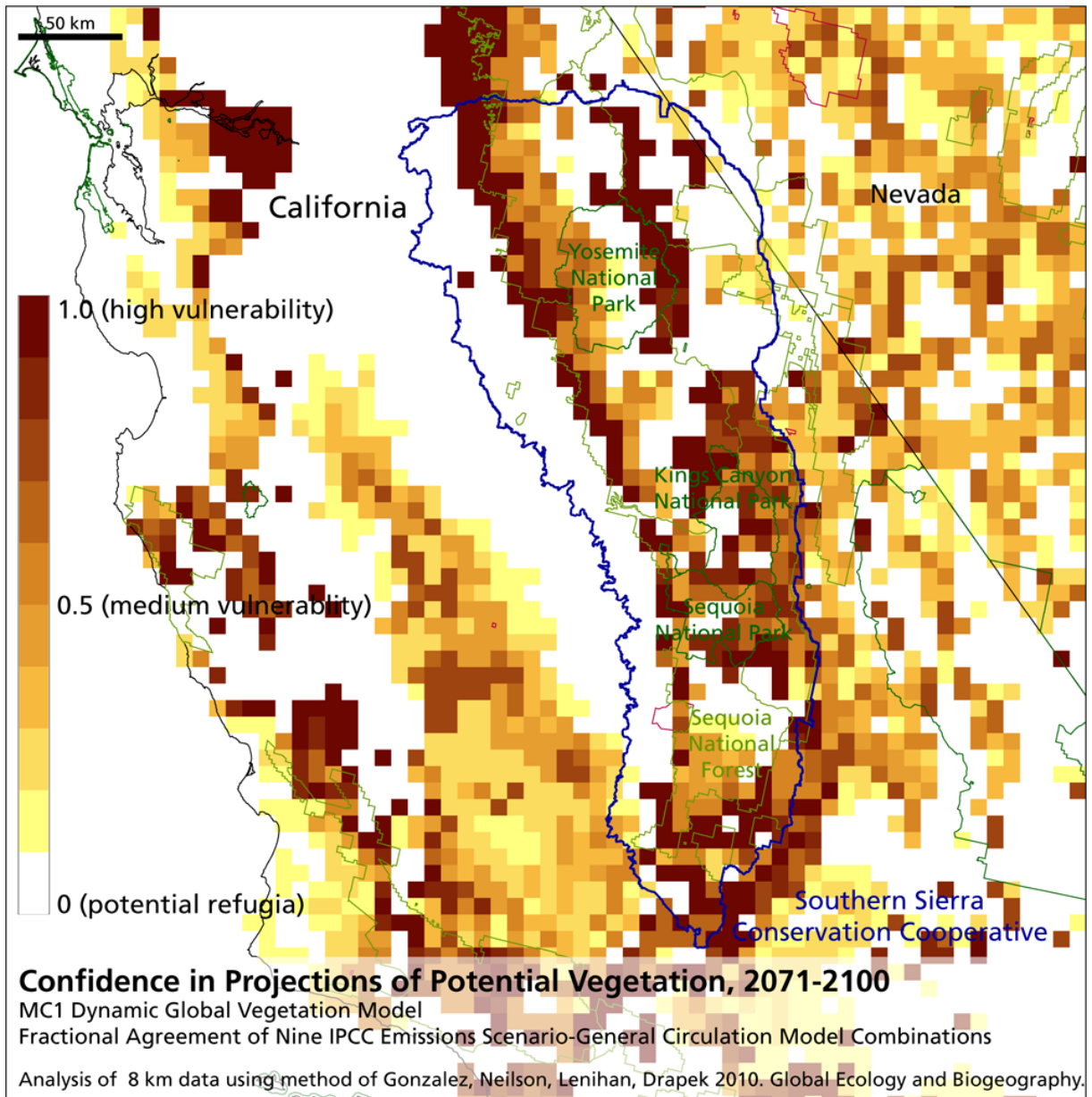
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