National Park Service
U.S. Department of the Interior

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

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

Patrick Gonzalez, Ph.D.

Climate Change Response Program
Natural Resource Stewardship and Science
National Park Service
1201 I Street NW
Washington, DC 20005-5905 USA

August 29, 2012

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 ± 0.2ºC 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 ºC $century^{-1}$ 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.

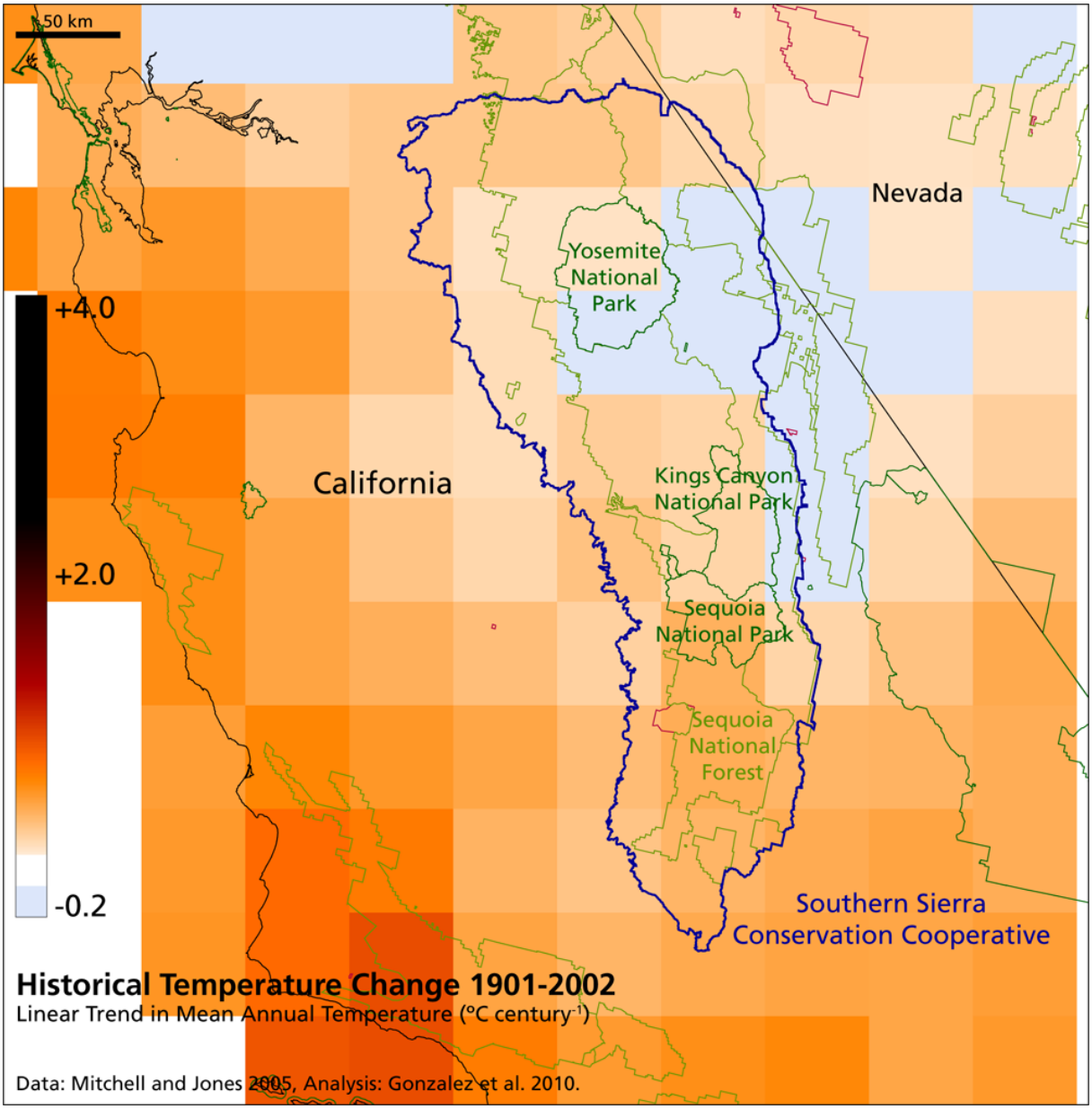

50 km
+4.0
+2.0
-0.2
Nevada
California
Yosemite National Park
Kings Canyon National Park
Sequoia National Park
Sequoia National Forest
Southern Sierra Conservation Cooperative
Historical Temperature Change 1901-2002
Linear Trend in Mean Annual Temperature (°C century-1)
Data: Mitchell and Jones 2005, Analysis: Gonzalez et al. 2010.

Figure 2.

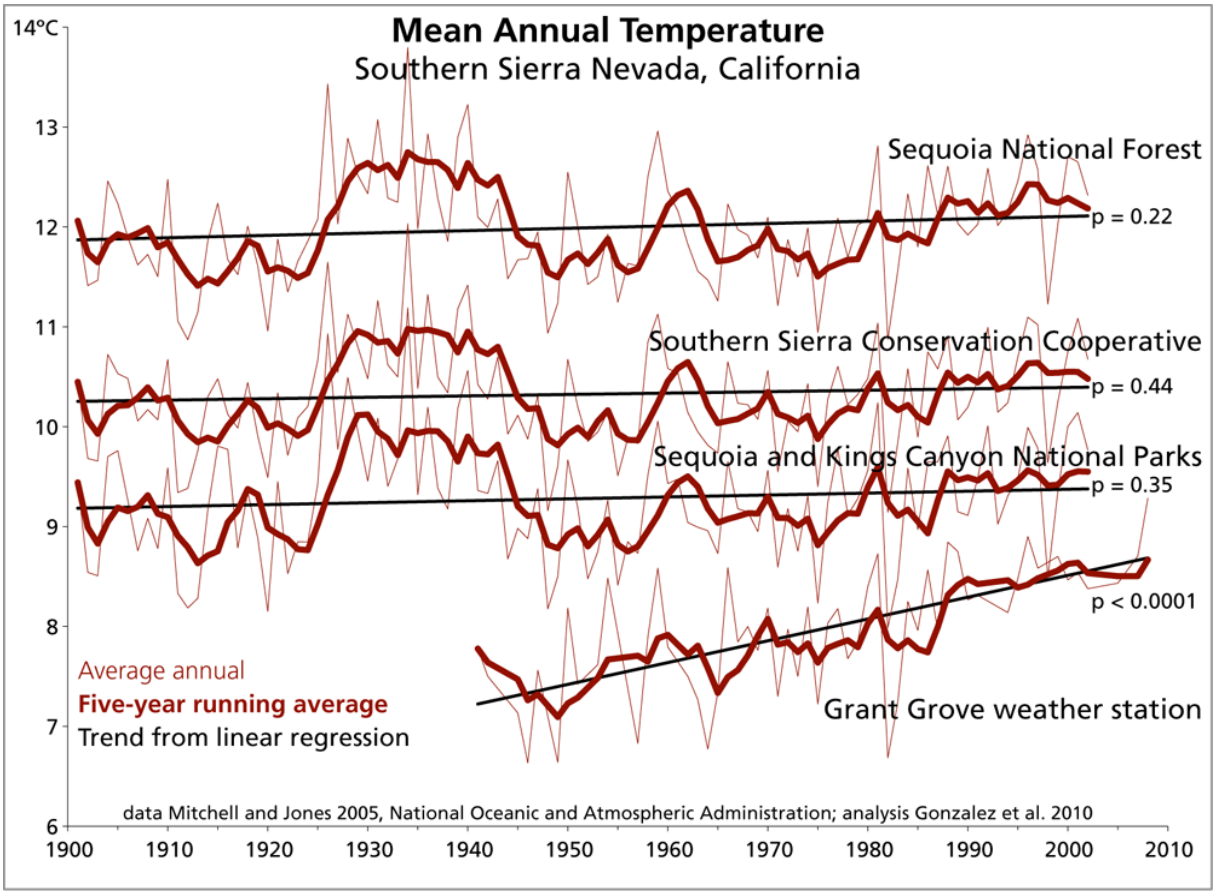

Mean Annual Temperature
Southern Sierra Nevada, California
14°C
13
12
11
10
9
8
7
6
Sequoia National Forest
p = 0.22
Southern Sierra Conservation Cooperative
p = 0.44
Sequoia and Kings Canyon National Parks
p = 0.35
p < 0.0001
Grant Grove weather station
Average annual
Five-year running average
Trend from linear regression
data Mitchell and Jones 2005, National Oceanic and Atmospheric Administration; analysis Gonzalez et al. 2010
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

Figure 3.

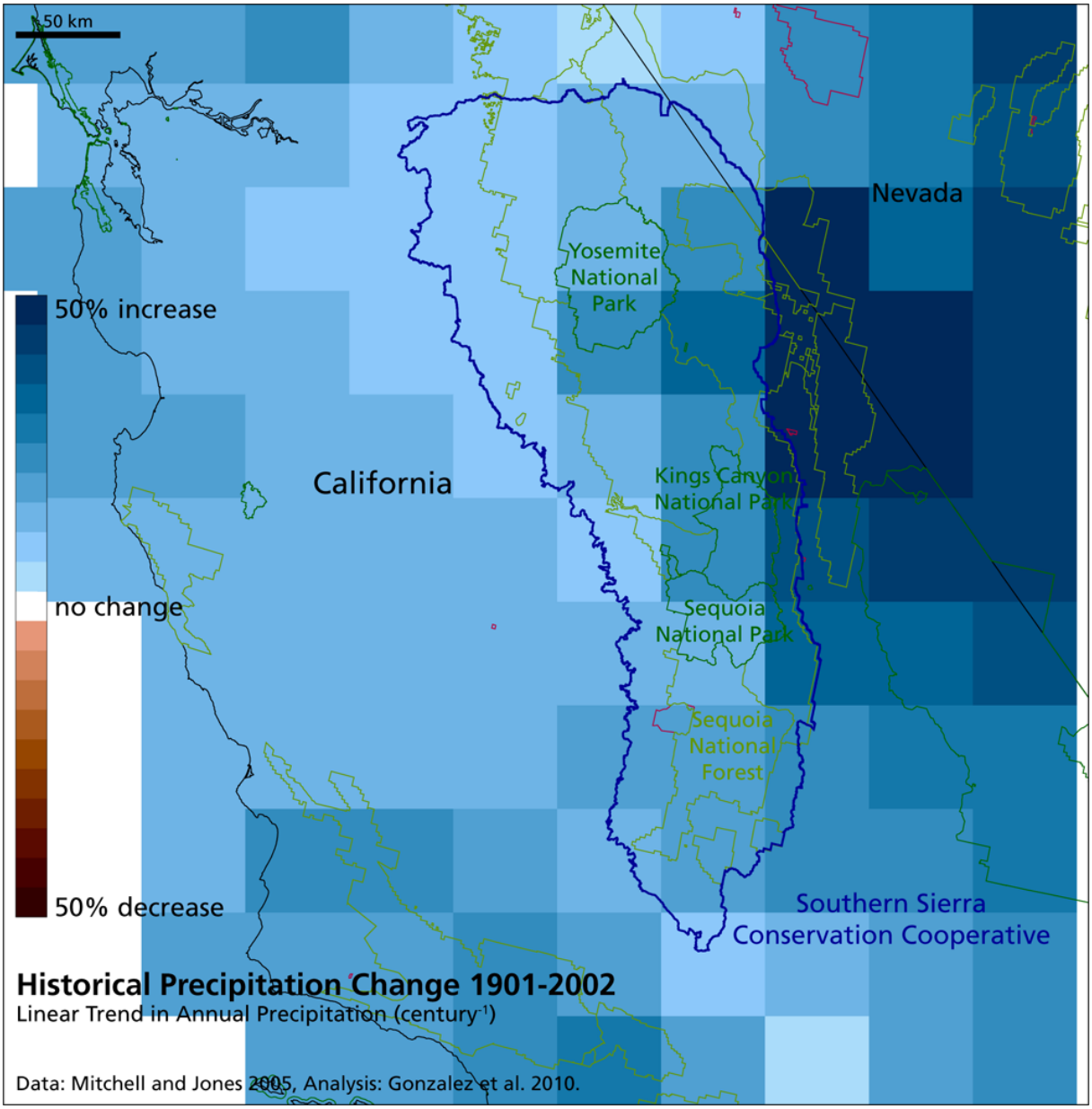

50 km
Nevada
Yosemite National Park
50% increase
California
Kings Canyon National Park
no change
Sequoia National Park
Sequoia National Forest
50% decrease
Southern Sierra Conservation Cooperative
Historical Precipitation Change 1901-2002
Linear Trend in Annual Precipitation (century-1)
Data: Mitchell and Jones 2005, Analysis: Gonzalez et al. 2010.

Figure 4.

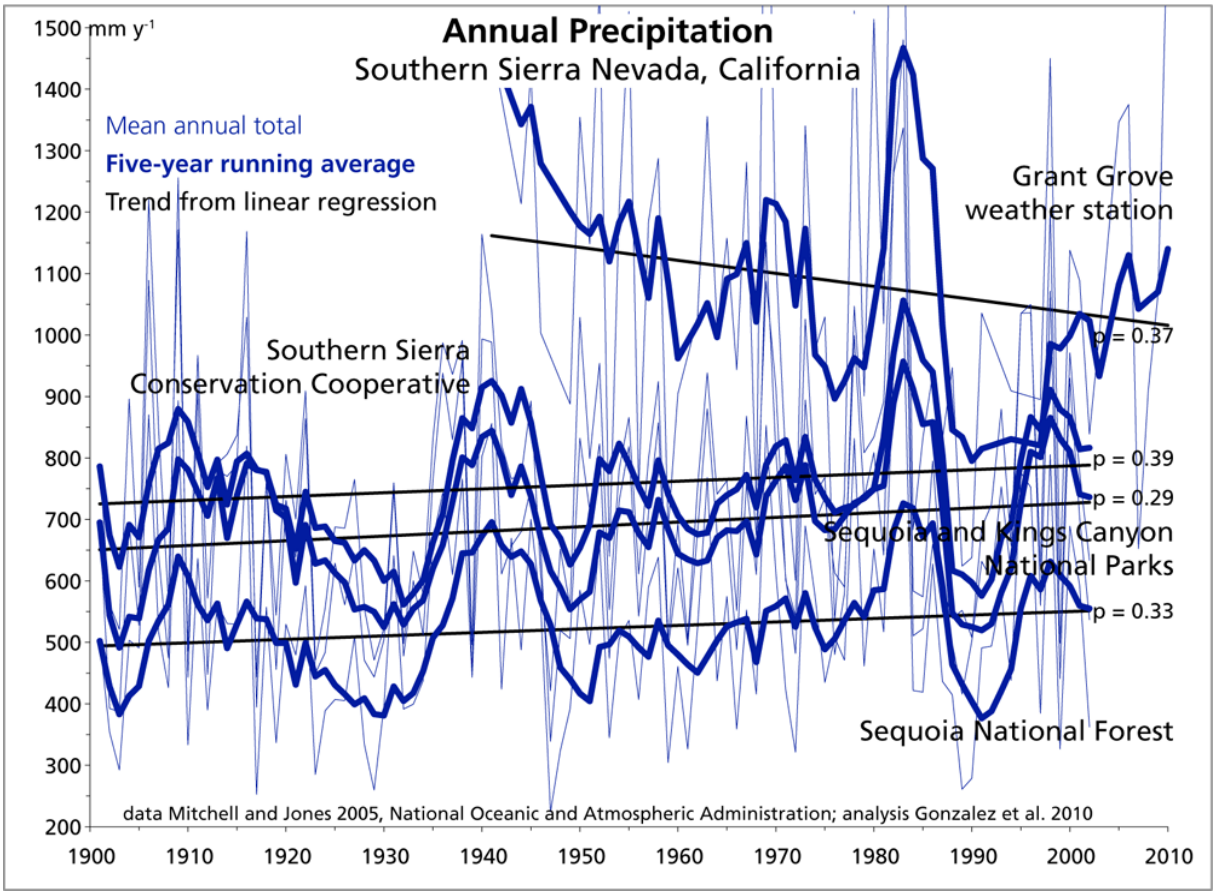

Annual Precipitation
Southern Sierra Nevada, California
mm y-1
Mean annual total
Five-year running average
Trend from linear regression
Grant Grove
weather station
p = 0.37
Southern Sierra
Conservation Cooperative
p = 0.39
p = 0.29
Sequoia and Kings Canyon
National Parks
p = 0.33
Sequoia National Forest
data Mitchell and Jones 2005, National Oceanic and Atmospheric Administration; analysis Gonzalez et al. 2010
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

Figure 5.

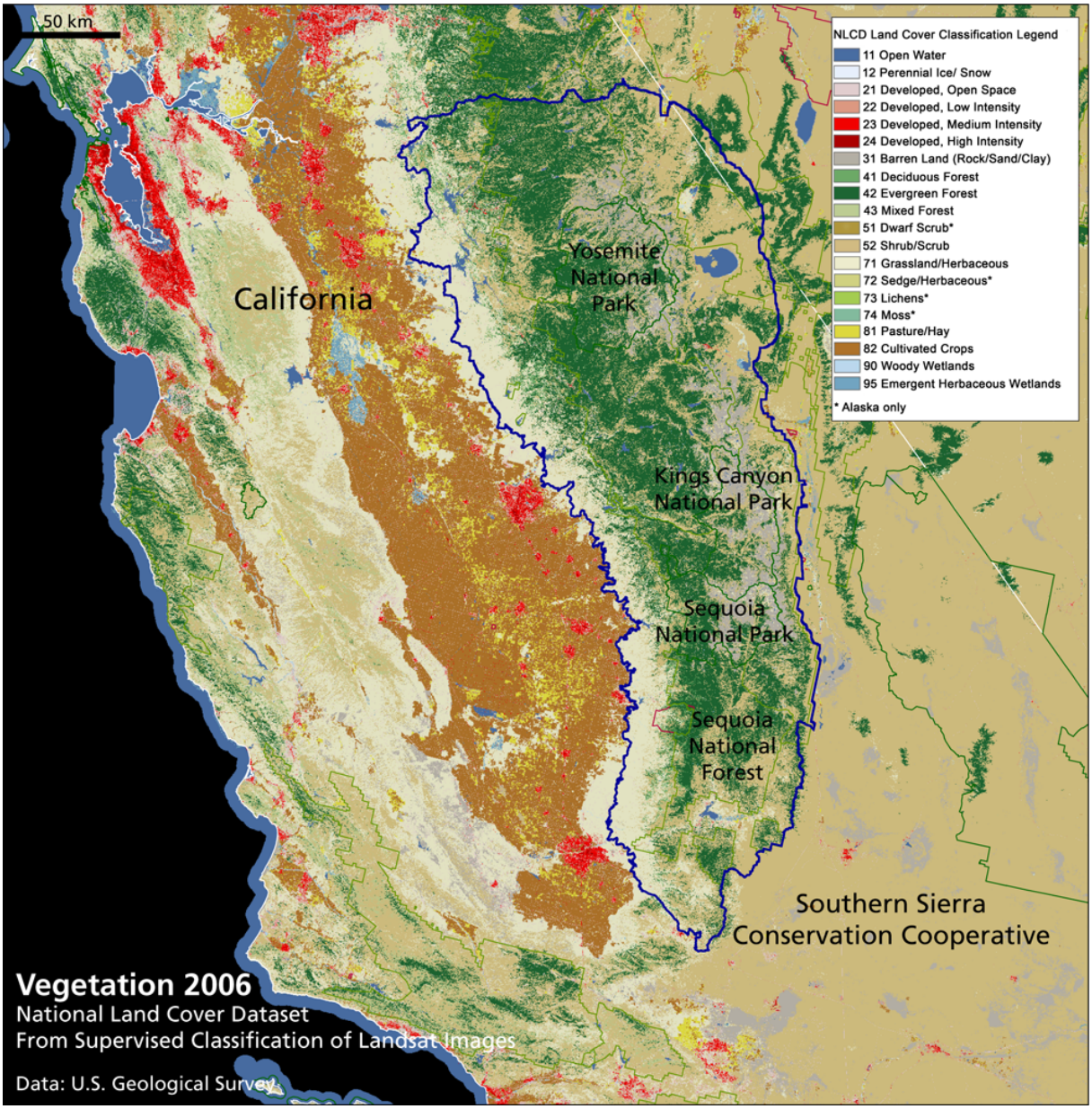

50 km
NLCD Land Cover Classification Legend
11 Open Water
12 Perennial Ice/ Snow
21 Developed, Open Space
22 Developed, Low Intensity
23 Developed, Medium Intensity
24 Developed, High Intensity
31 Barren Land (Rock/Sand/Clay)
41 Deciduous Forest
42 Evergreen Forest
43 Mixed Forest
51 Dwarf Scrub*
52 Shrub/Scrub
71 Grassland/Herbaceous
72 Sedge/Herbaceous*
73 Lichens*
74 Moss*
81 Pasture/Hay
82 Cultivated Crops
90 Woody Wetlands
95 Emergent Herbaceous Wetlands
* Alaska only
California
Yosemite National Park
Kings Canyon National Park
Sequoia National Park
Sequoia National Forest
Southern Sierra Conservation Cooperative
Vegetation 2006
National Land Cover Dataset
From Supervised Classification of Landsat Images
Data: U.S. Geological Survey

Figure 6.

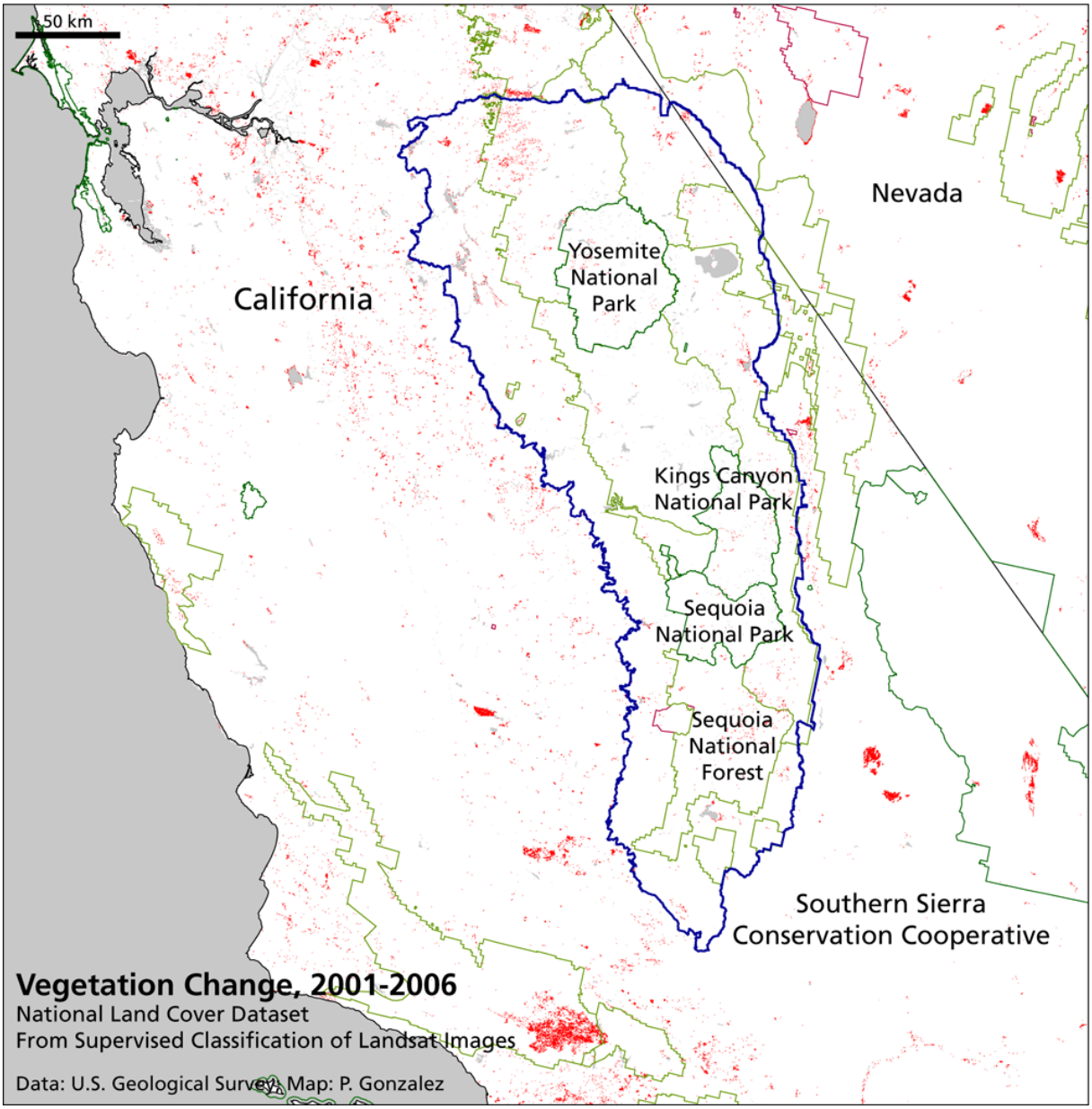

50 km
Nevada
California
Yosemite National Park
Kings Canyon National Park
Sequoia National Park
Sequoia National Forest
Southern Sierra Conservation Cooperative
Vegetation Change, 2001-2006
National Land Cover Dataset
From Supervised Classification of Landsat Images
Data: U.S. Geological Survey, Map: P. Gonzalez

Figure 7.

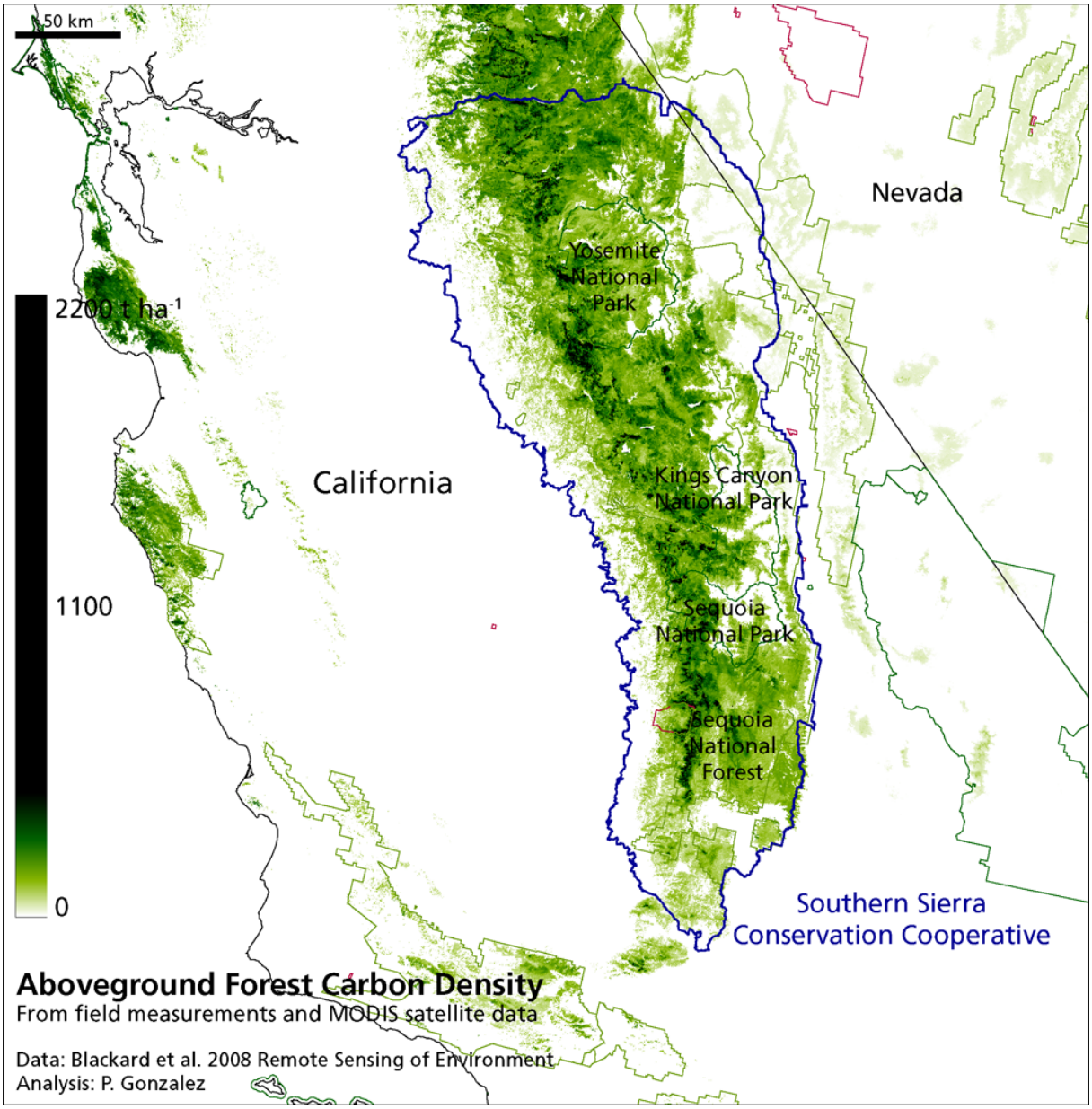

50 km
2200 t ha-1
1100
0
California
Nevada
Yosemite National Park
Kings Canyon National Park
Sequoia National Park
Sequoia National Forest
Southern Sierra Conservation Cooperative
Aboveground Forest Carbon Density
From field measurements and MODIS satellite data
Data: Blackard et al. 2008 Remote Sensing of Environment
Analysis: P. Gonzalez

Figure 8.

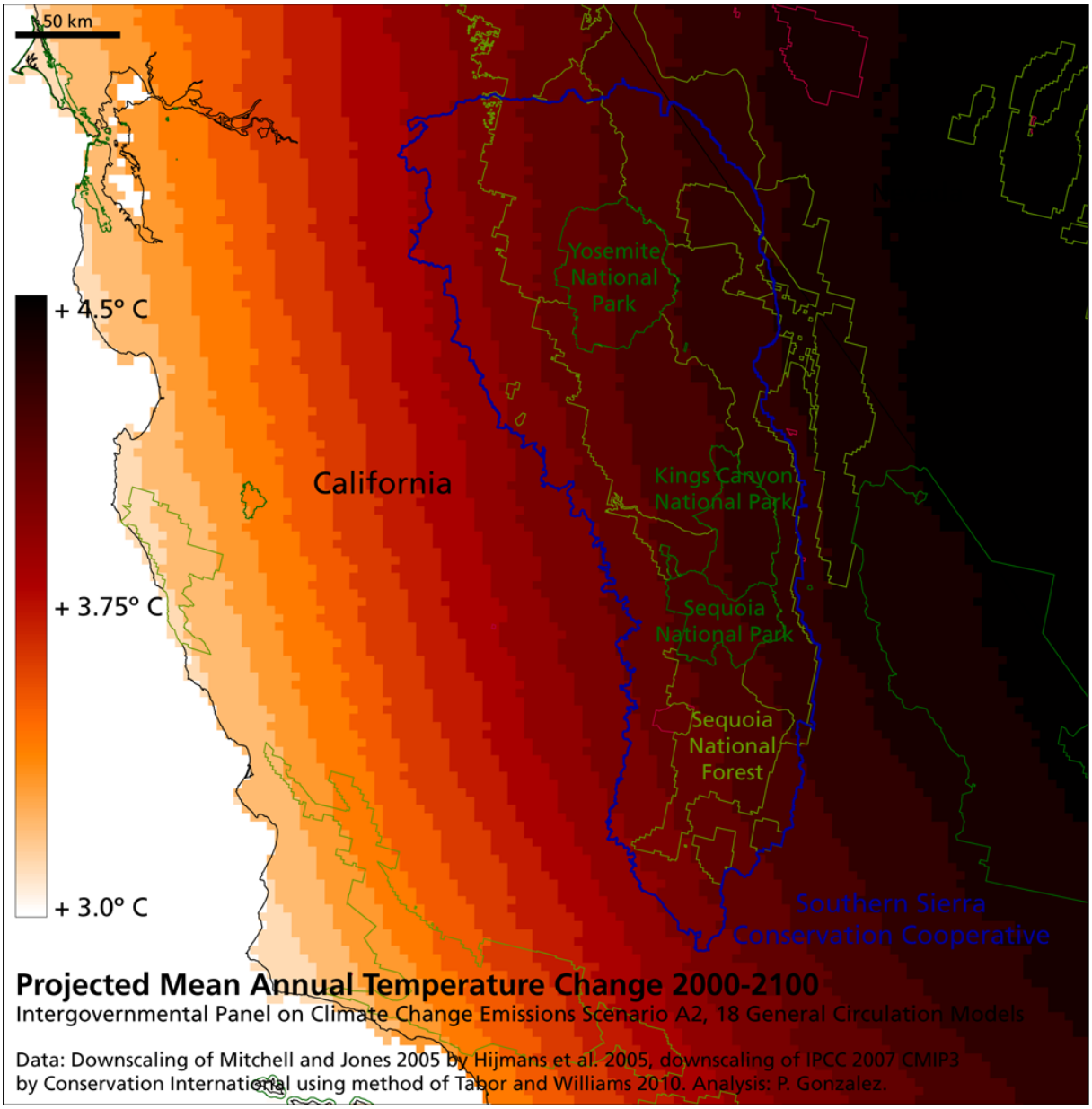

50 km
+ 4.5° C
+ 3.75° C
+ 3.0° C
California
Yosemite National Park
Kings Canyon National Park
Sequoia National Park
Sequoia National Forest
Southern Sierra Conservation Cooperative
Projected Mean Annual Temperature Change 2000-2100
Intergovernmental Panel on Climate Change Emissions Scenario A2, 18 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 9.

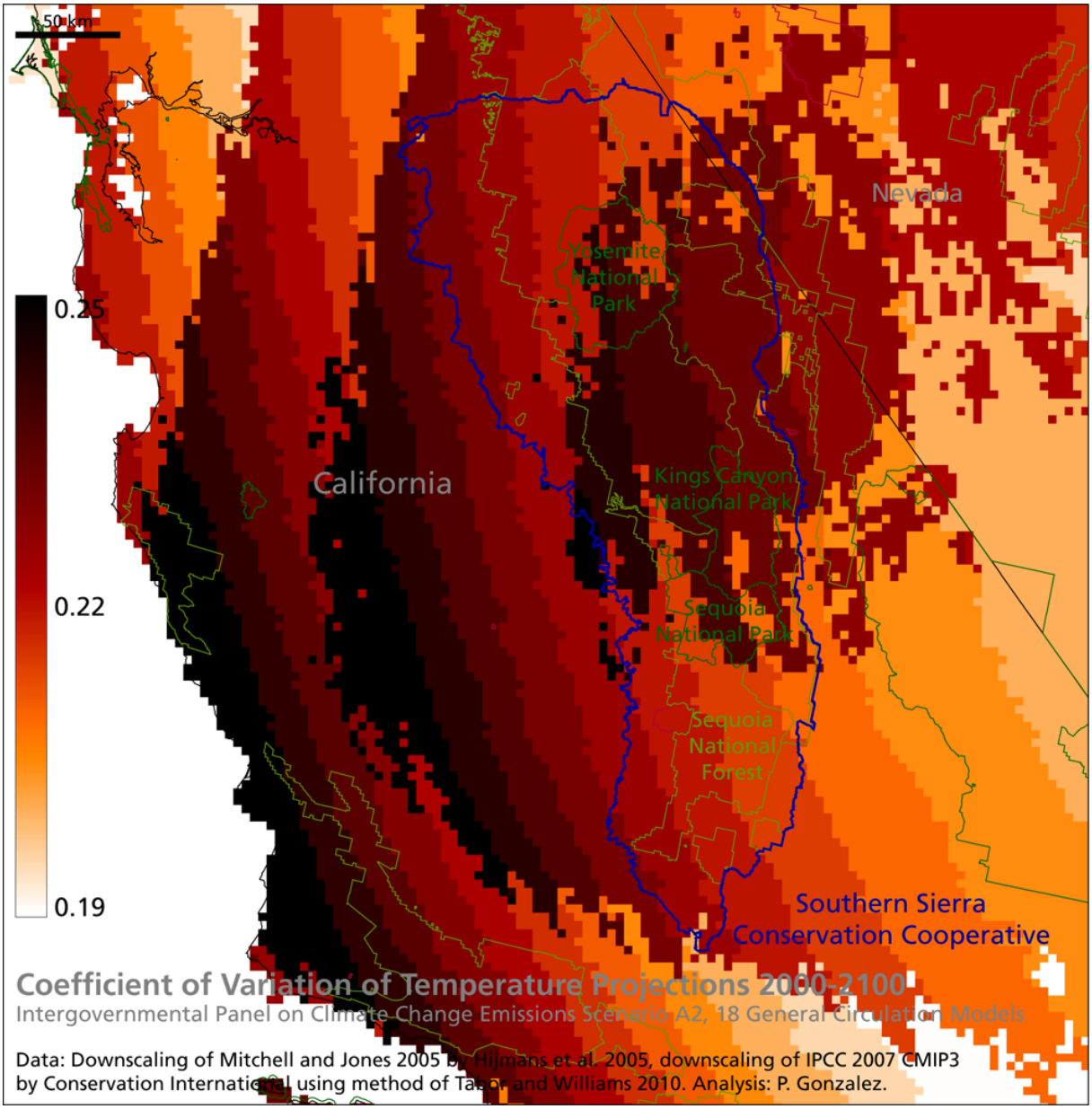

50 km
0.25
0.22
0.19
California
Nevada
Yosemite National Park
Kings Canyon National Park
Sequoia National Park
Sequoia National Forest
Southern Sierra Conservation Cooperative
Coefficient of Variation of Temperature Projections 2000-2100
Intergovernmental Panel on Climate Change Emissions Scenario A2, 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 10.

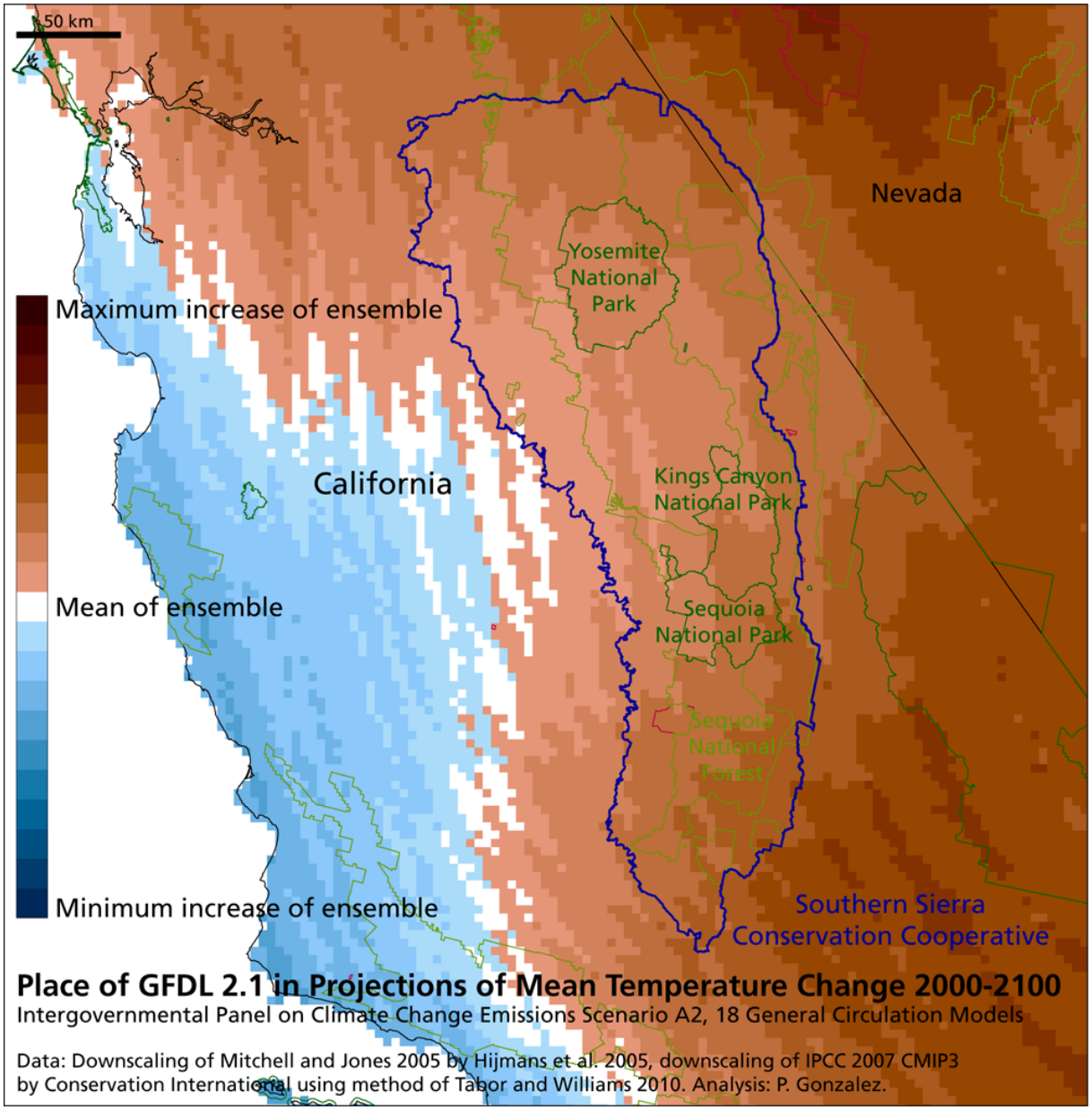

50 km
Nevada
Yosemite National Park
Maximum increase of ensemble
California
Kings Canyon National Park
Mean of ensemble
Sequoia National Park
Sequoia National Forest
Minimum increase of ensemble
Southern Sierra Conservation Cooperative
Place of GFDL 2.1 in Projections of Mean Temperature Change 2000-2100
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 11.

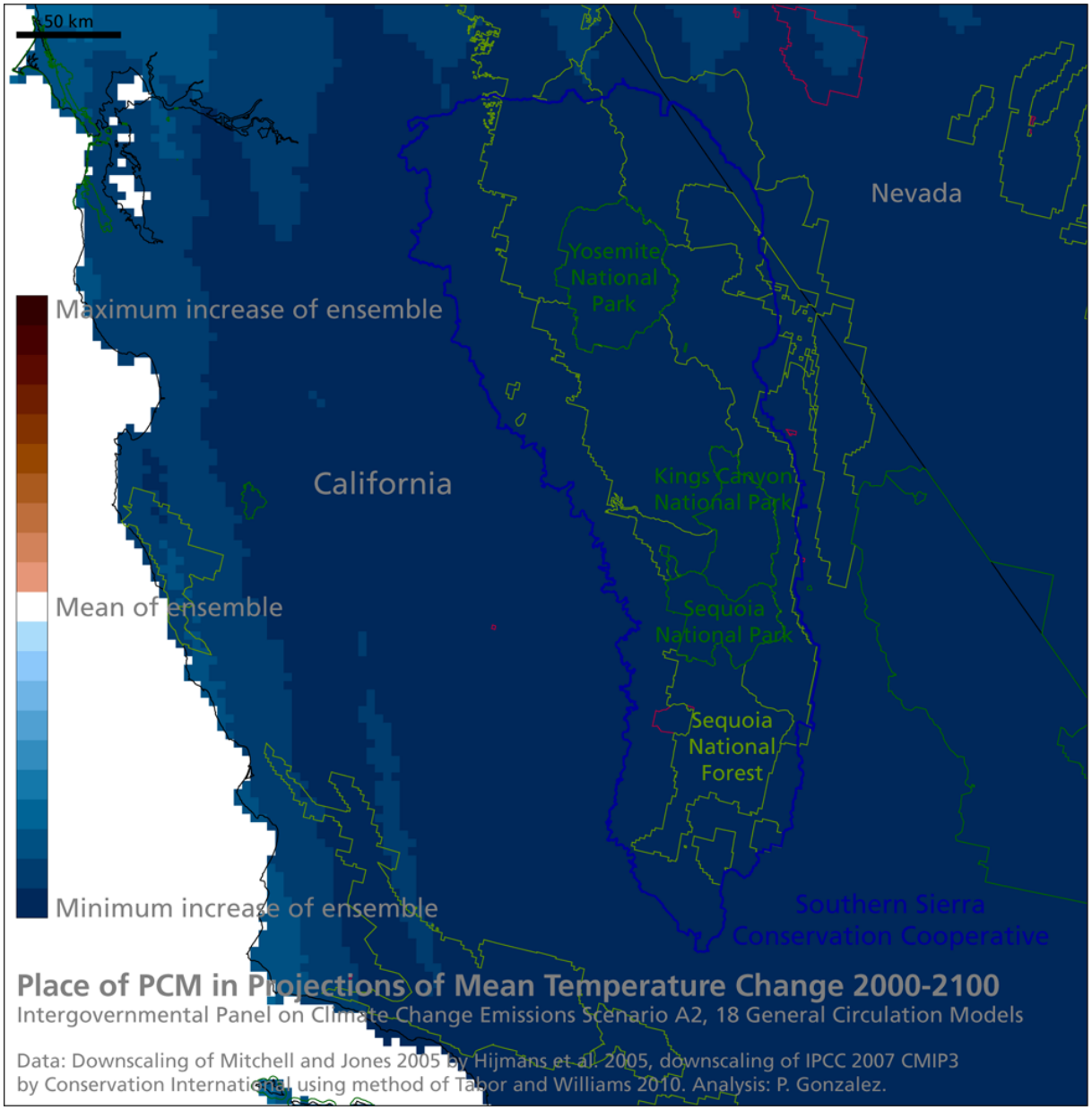

50 km
Nevada
Yosemite National Park
Maximum increase of ensemble
California
Kings Canyon National Park
Mean of ensemble
Sequoia National Park
Sequoia National Forest
Minimum increase of ensemble
Southern Sierra Conservation Cooperative
Place of PCM in Projections of Mean Temperature Change 2000-2100
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 12.

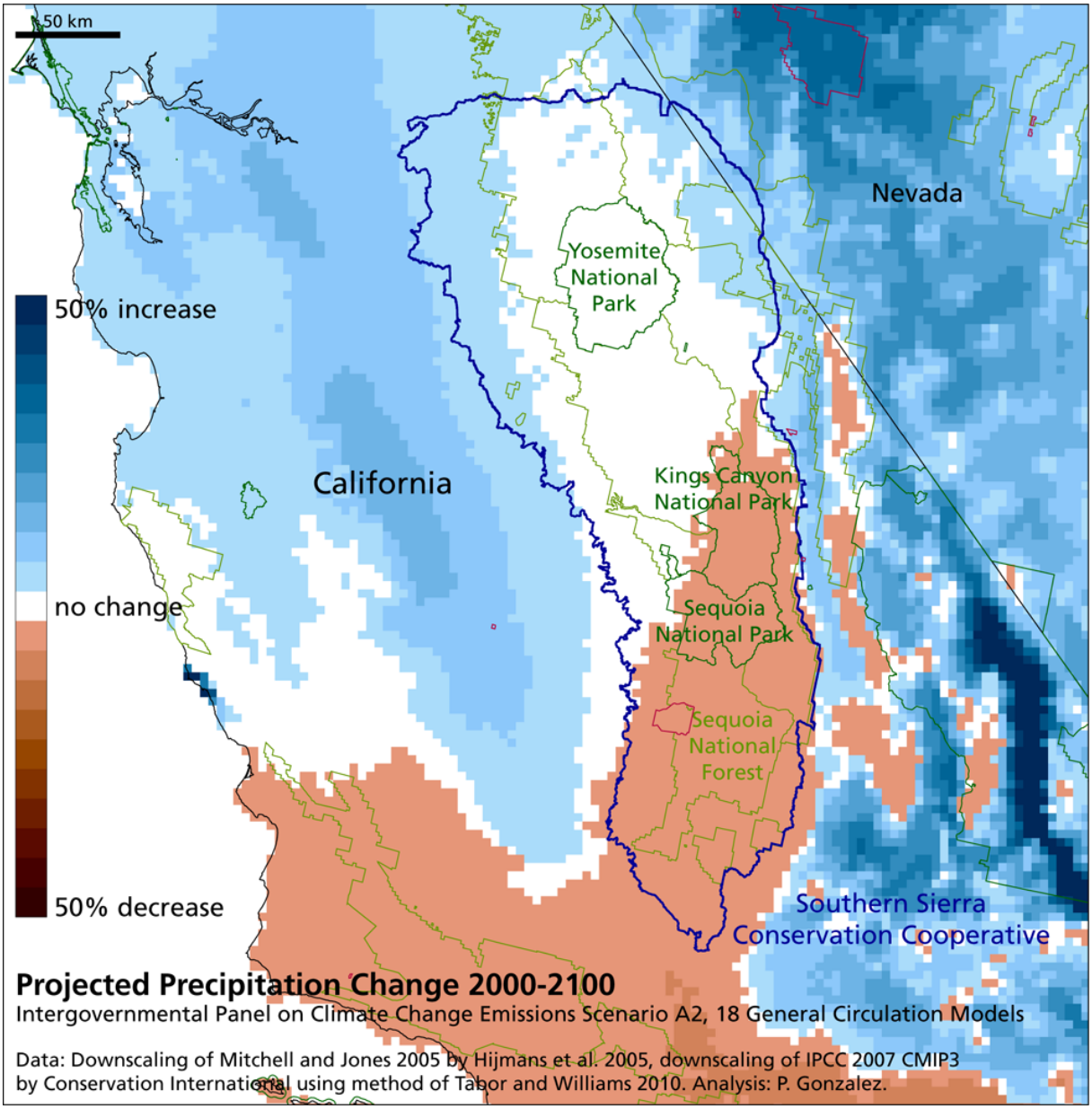

50 km
Nevada
Yosemite National Park
50% increase
California
Kings Canyon National Park
no change
Sequoia National Park
Sequoia National Forest
50% decrease
Southern Sierra Conservation Cooperative
Projected Precipitation Change 2000-2100
Intergovernmental Panel on Climate Change Emissions Scenario A2, 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.

Figure 13.

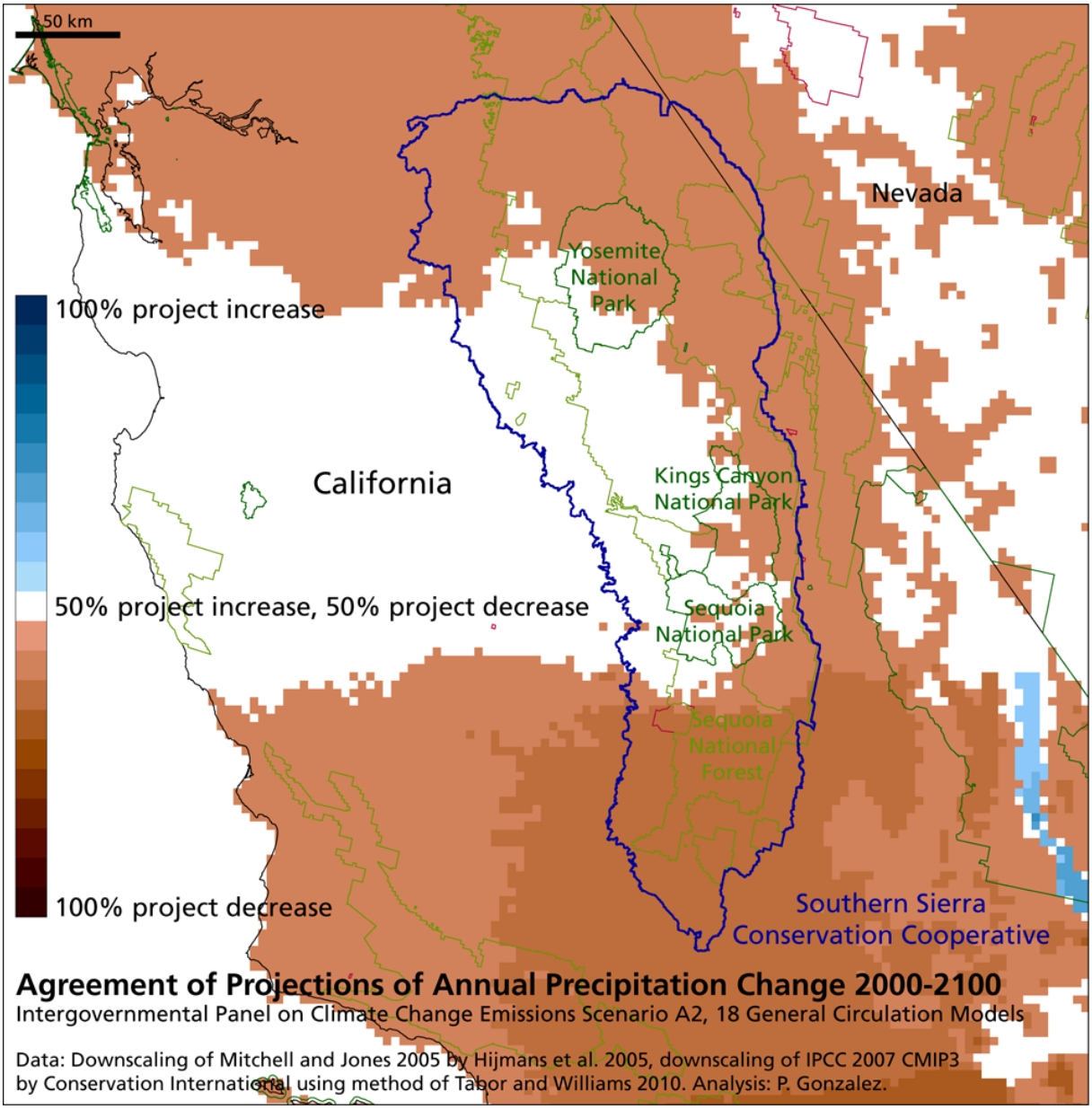

50 km
Nevada
Yosemite National Park
100% project increase
California
Kings Canyon National Park
50% project increase, 50% project decrease
Sequoia National Park
Sequoia National Forest
100% project decrease
Southern Sierra Conservation Cooperative
Agreement of Projections of Annual Precipitation Change 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.

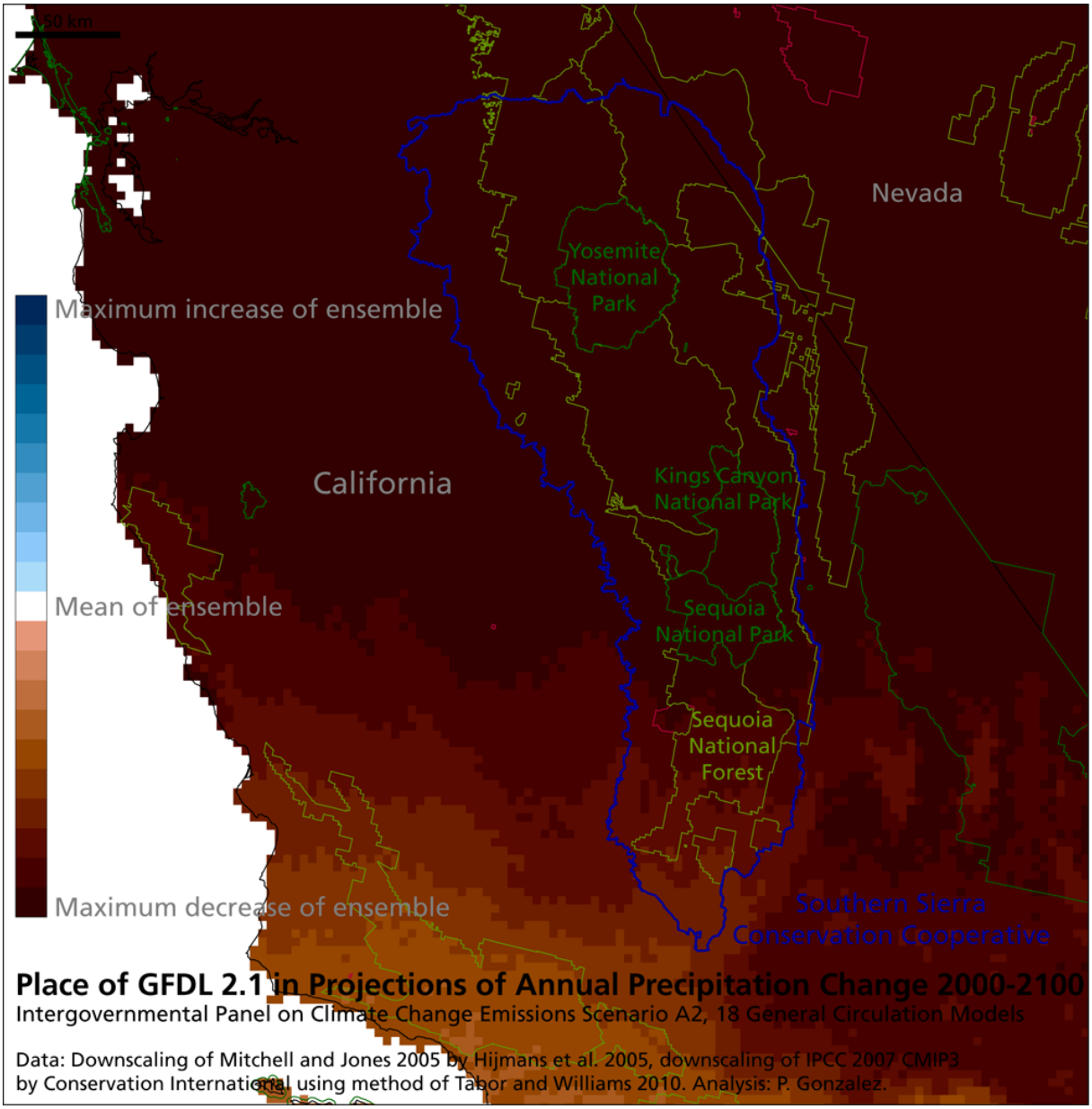

50 km
Nevada
Yosemite National Park
Maximum increase of ensemble
California
Kings Canyon National Park
Mean of ensemble
Sequoia National Park
Sequoia National Forest
Maximum decrease of ensemble
Southern Sierra Conservation Cooperative
Place of GFDL 2.1 in Projections of Annual Precipitation Change 2000-2100
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 15.

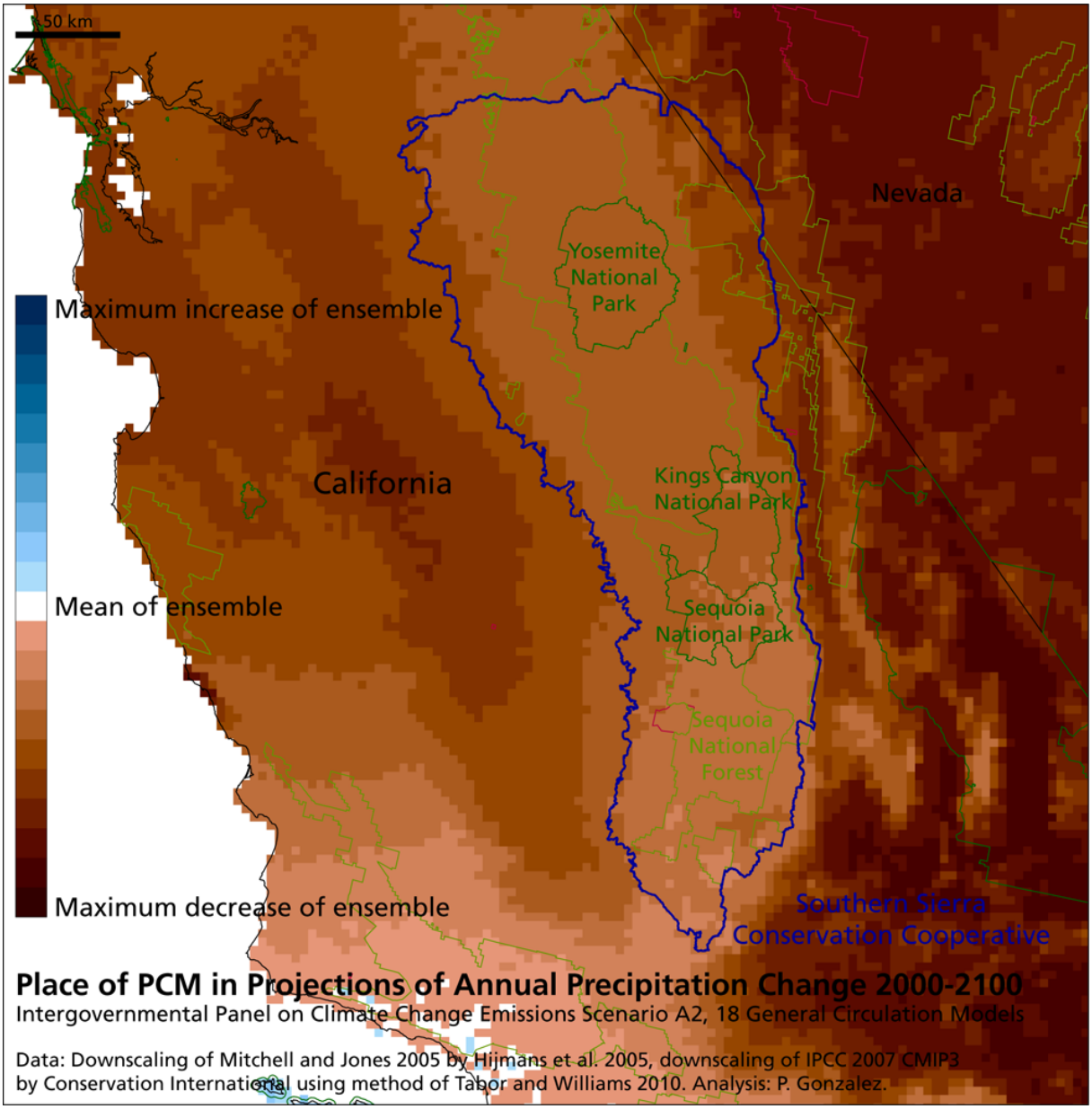

50 km
Nevada
Yosemite National Park
Maximum increase of ensemble
California
Kings Canyon National Park
Mean of ensemble
Sequoia National Park
Sequoia National Forest
Maximum decrease of ensemble
Southern Sierra Conservation Cooperative
Place of PCM in Projections of Annual Precipitation Change 2000-2100
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.

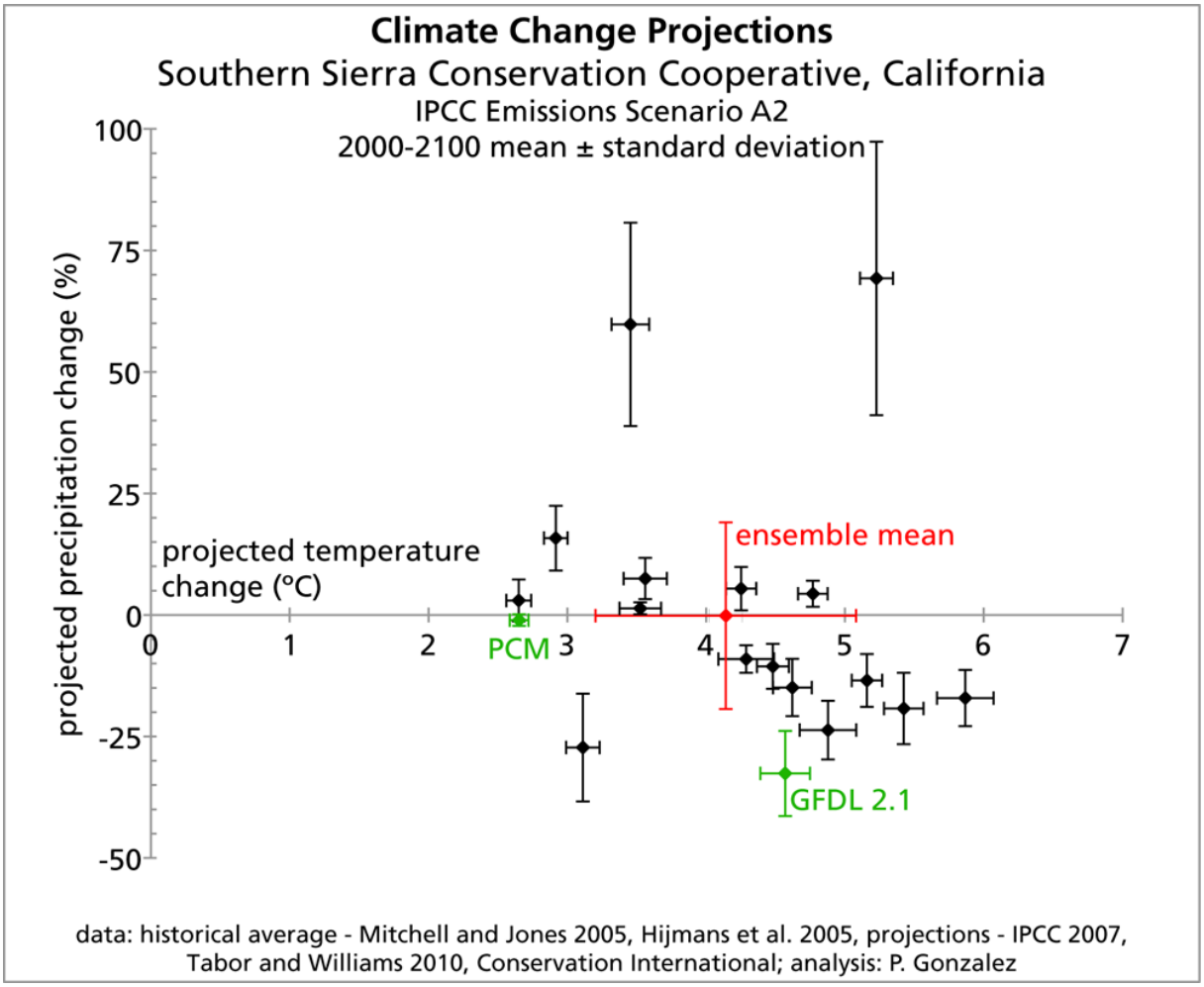

Climate Change Projections
Southern Sierra Conservation Cooperative, California
IPCC Emissions Scenario A2
2000-2100 mean ± standard deviation
projected precipitation change (%)
100
75
50
25
0
-25
-50
projected temperature change (°C)
0
1
2
3
4
5
6
7
PCM
ensemble mean
GFDL 2.1
data: historical average - Mitchell and Jones 2005, Hijmans et al. 2005, projections - IPCC 2007, Tabor and Williams 2010, Conservation International; analysis: P. Gonzalez

Figure 17.

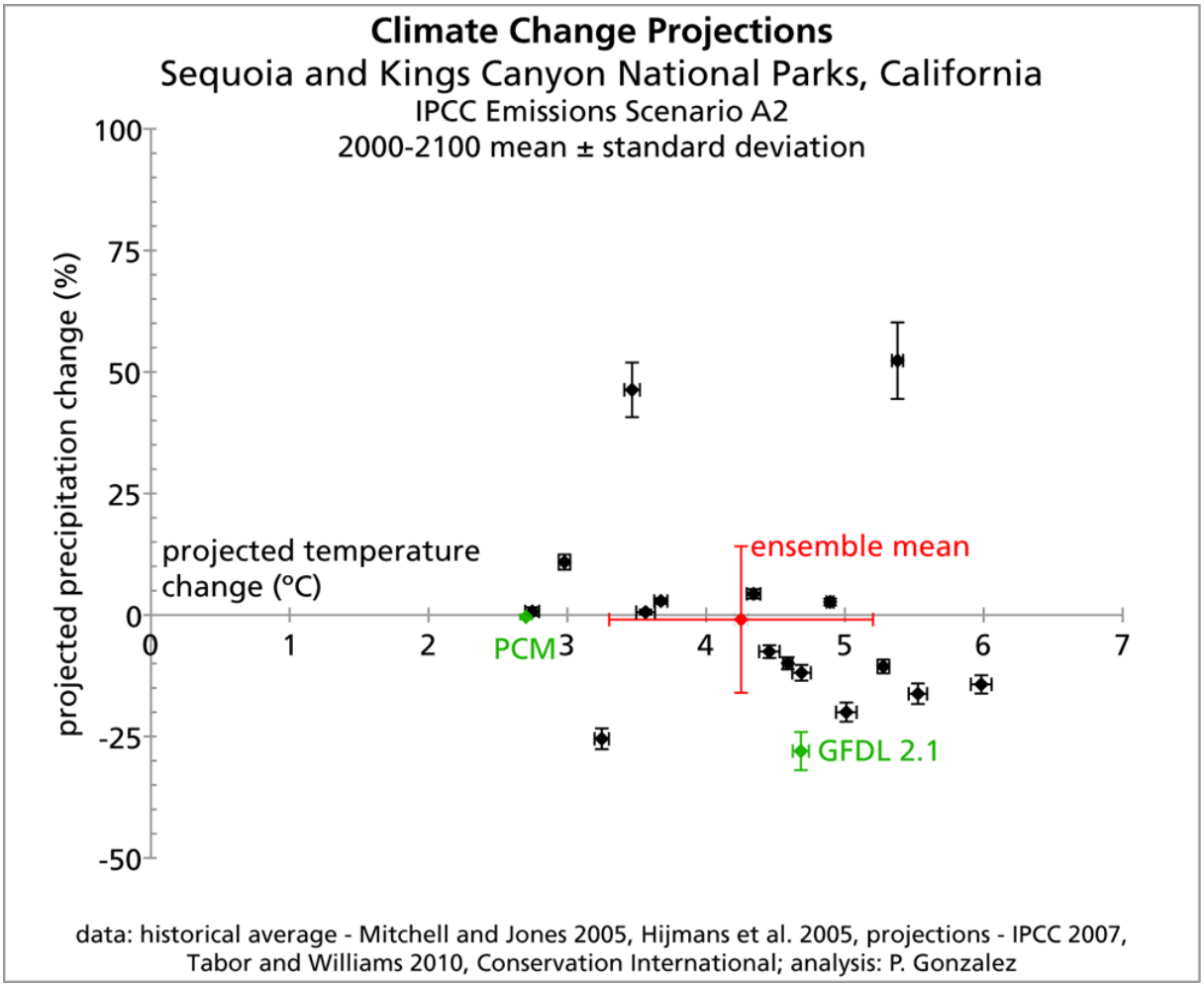

Climate Change Projections
Sequoia and Kings Canyon National Parks, California
IPCC Emissions Scenario A2
2000-2100 mean ± standard deviation
projected precipitation change (%)
100
75
50
25
0
-25
-50
projected temperature change (°C)
0
1
2
3
4
5
6
7
PCM
ensemble mean
GFDL 2.1
data: historical average - Mitchell and Jones 2005, Hijmans et al. 2005, projections - IPCC 2007, Tabor and Williams 2010, Conservation International; analysis: P. Gonzalez

Figure 18.

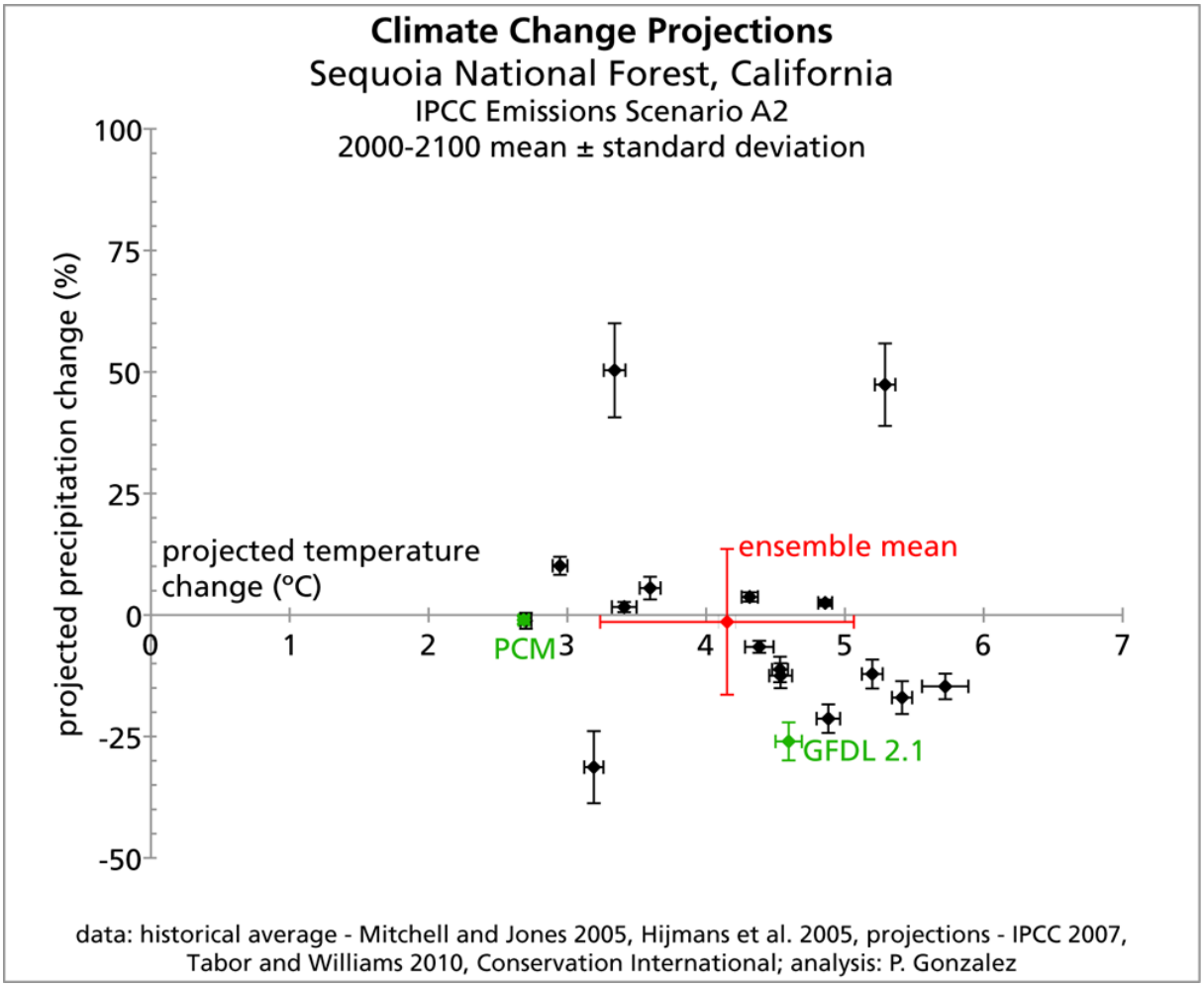

Climate Change Projections
Sequoia National Forest, California
IPCC Emissions Scenario A2
2000-2100 mean ± standard deviation
projected precipitation change (%)
100
75
50
25
0
-25
-50
projected temperature change (°C)
0
1
2
3
4
5
6
7
PCM
ensemble mean
GFDL 2.1
data: historical average - Mitchell and Jones 2005, Hijmans et al. 2005, projections - IPCC 2007, Tabor and Williams 2010, Conservation International; analysis: P. Gonzalez

Figure 19.

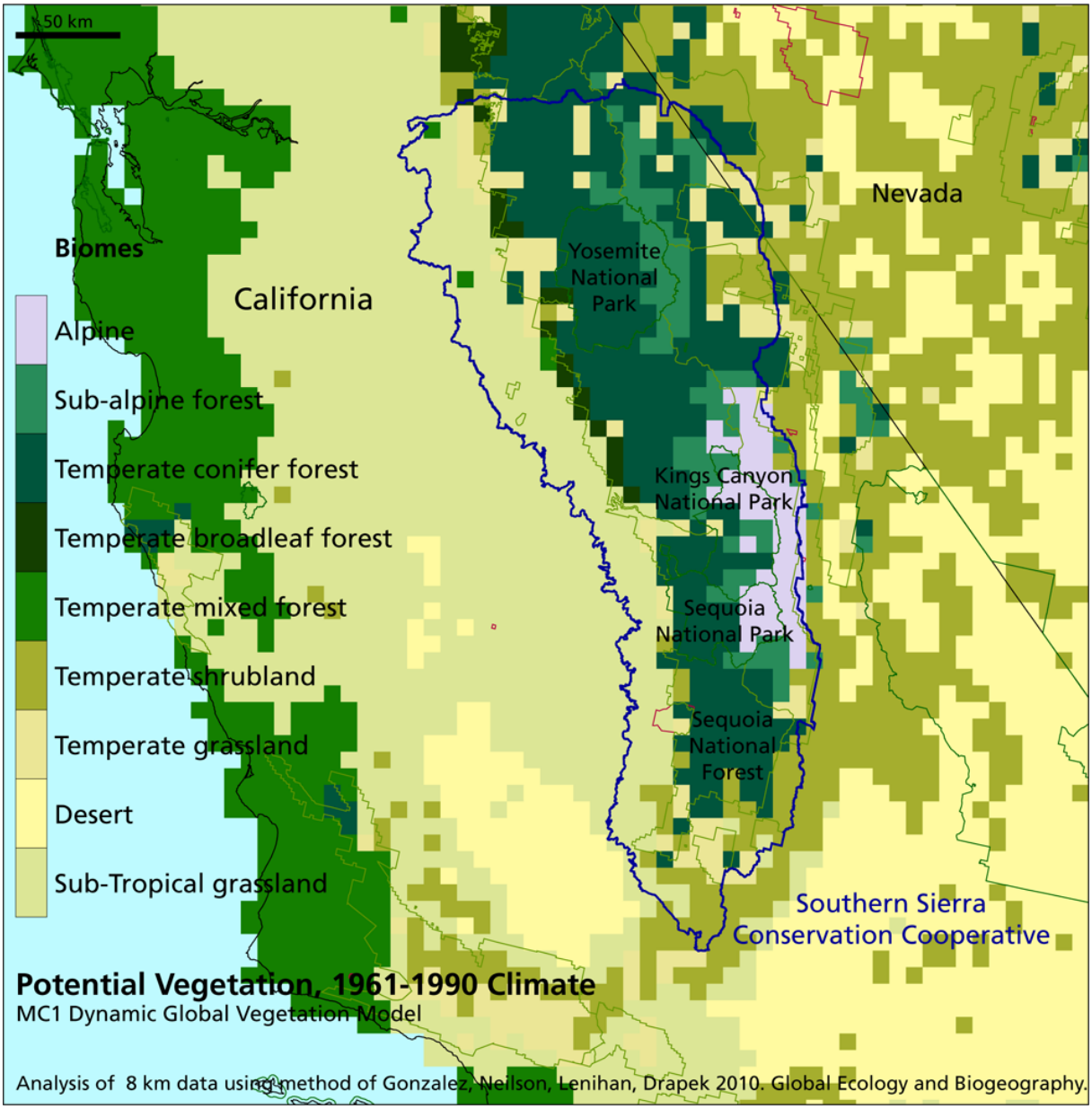

50 km
Biomes
Alpine
Sub-alpine forest
Temperate conifer forest
Temperate broadleaf forest
Temperate mixed forest
Temperate shrubland
Temperate grassland
Desert
Sub-Tropical grassland
California
Nevada
Yosemite National Park
Kings Canyon National Park
Sequoia National Park
Sequoia National Forest
Southern Sierra Conservation Cooperative
Potential Vegetation, 1961-1990 Climate
MC1 Dynamic Global Vegetation Model
Analysis of 8 km data using method of Gonzalez, Neilson, Lenihan, Drapek 2010. Global Ecology and Biogeography.

Figure 20.

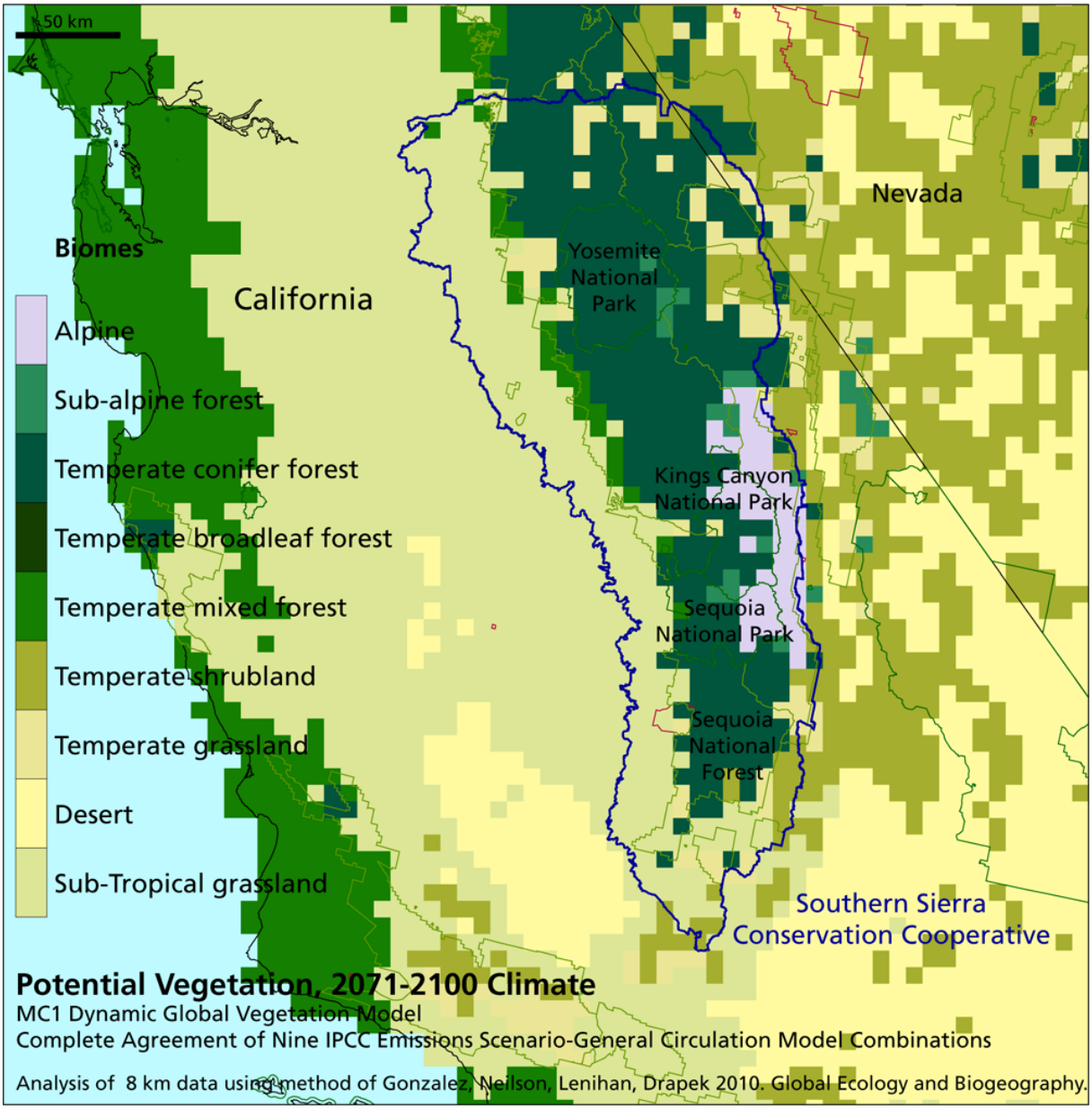

50 km
Biomes
Alpine
Sub-alpine forest
Temperate conifer forest
Temperate broadleaf forest
Temperate mixed forest
Temperate shrubland
Temperate grassland
Desert
Sub-Tropical grassland
California
Nevada
Yosemite National Park
Kings Canyon National Park
Sequoia National Park
Sequoia National Forest
Southern Sierra Conservation Cooperative
Potential Vegetation, 2071-2100 Climate
MC1 Dynamic Global Vegetation Model
Complete 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.

Figure 21.

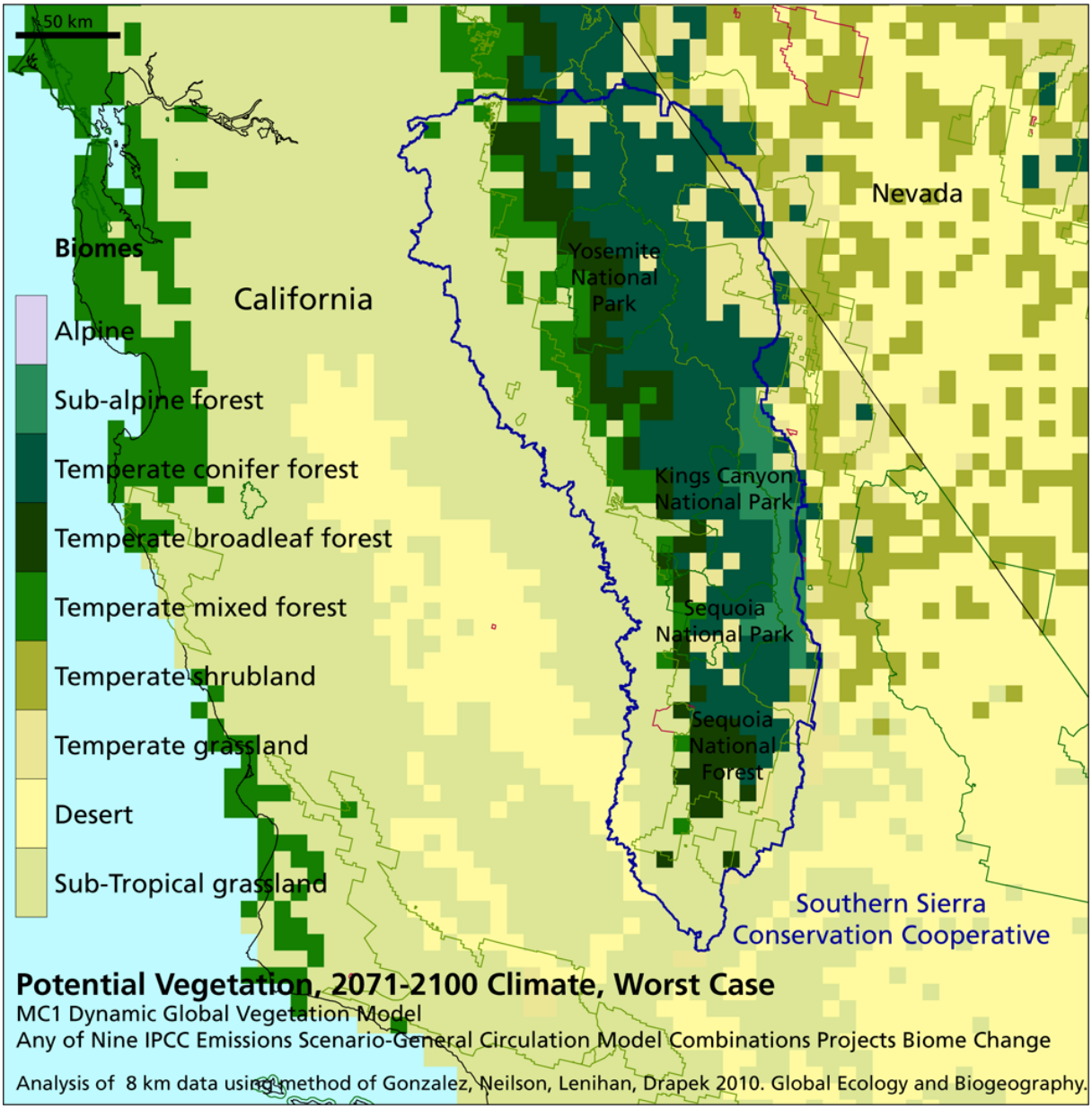
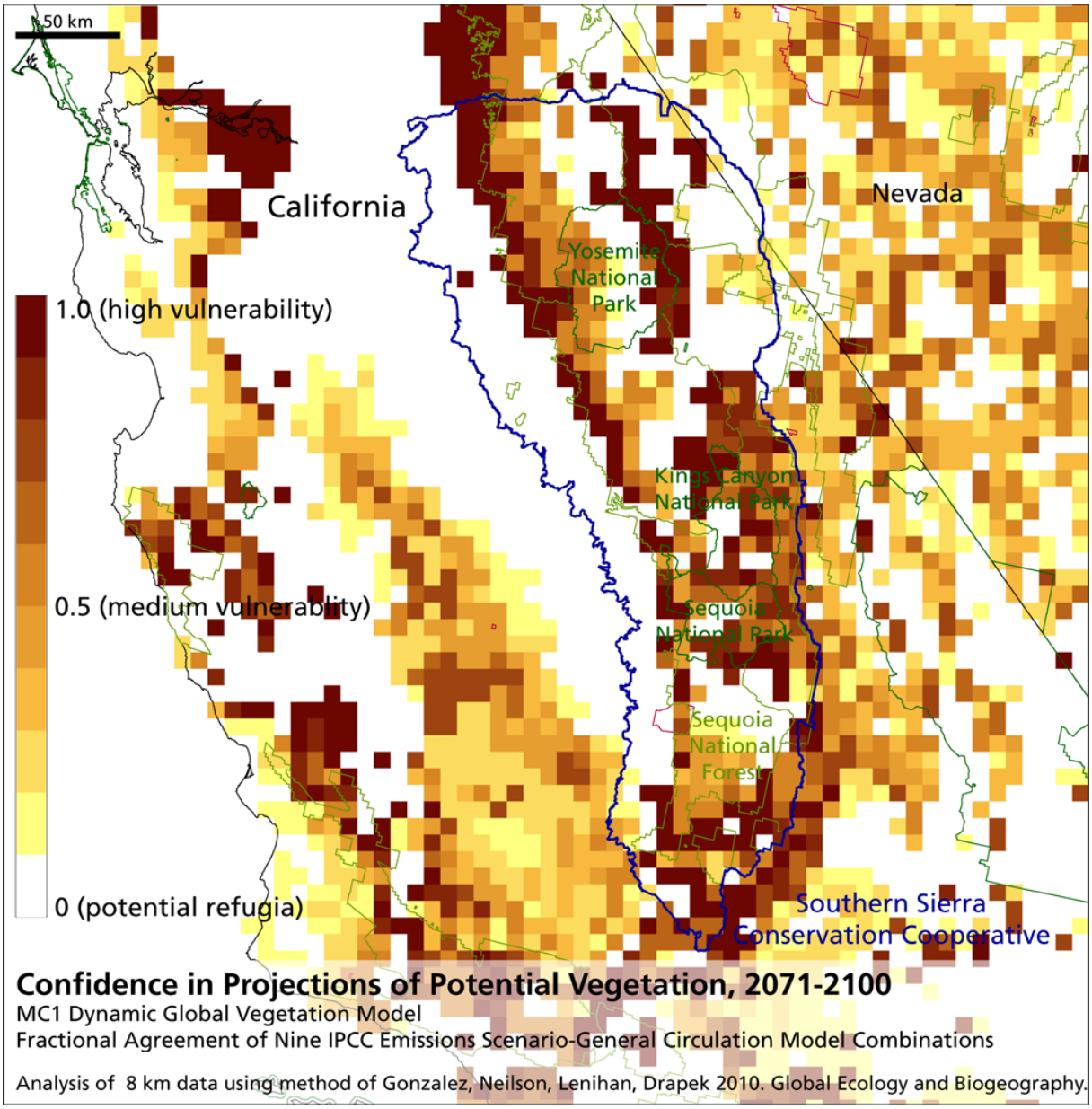

50 km
Biomes
Alpine
Sub-alpine forest
Temperate conifer forest
Temperate broadleaf forest
Temperate mixed forest
Temperate shrubland
Temperate grassland
Desert
Sub-Tropical grassland
California
Nevada
Yosemite National Park
Kings Canyon National Park
Sequoia National Park
Sequoia National Forest
Southern Sierra Conservation Cooperative
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.


50 km
California
Nevada
Yosemite National Park
Kings Canyon National Park
Sequoia National Park
Sequoia National Forest
Southern Sierra Conservation Cooperative
1.0 (high vulnerability)
0.5 (medium vulnerablity)
0 (potential refugia)
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.

References

Aalde, H., P. Gonzalez, M. Gytarsky, T. Krug, W.A. Kurz, S. Ogle, J. Raison, D. Schoene, N.H. Ravindranath, N.G. Elhassan, L.S. Heath, N. Higuchi, S. Kainja, M. Matsumoto, M.J.S. Sánchez, and Z. Somogyi. 2006. Forest Land. In Intergovernmental Panel on Climate Change. National Greenhouse Gas Inventory Guidelines. Institute for Global Environmental Strategies, Hayama, Japan.

Anderson, R.S. 1996. Postglacial biogeography of Sierra lodgepole pine (Pinus contorta var. murrayana) in California. Ecoscience 3: 343-351.

Ault, T.R., A.K. Macalady, G.T. Pederson, J.L. Betancourt, and M.D. Schwartz. 2011. Northern Hemisphere modes of variability and the timing of spring in western North America. Journal of Climate 24: 4003-4014.

Baker, T.R., O.L. Phillips, Y. Malhi, S. Almeida, L. Arroyo, A. Di Fiore, T. Erwin, N. Higuchi, T.J. Killeen, S.G. Laurance, W.F. Laurance, S.L. Lewis, A. Monteagudo, D.A. Neill, P.N. Vargas, N.C.A. Pitman, J.N.M. Silva, and R.V. Martínez. 2004. Increasing biomass in Amazonian forest plots. Philosophical Transactions of the Royal Society of London B 359: 353-365.

Barnett, T.P., D.W. Pierce, H.G. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood, T. Nozawa, A.A. Mirin, D.R. Cayan, and M.D. Dettinger. 2008. Human-induced changes in the hydrology of the western United States. Science 319: 1080-1083.

Blackard, J.A., M.V. Finco, E.H. Helmer, G.R. Holden, M.L. Hoppus, D.M. Jacobs, A.J. Lister, G.G. Moisen, M.D. Nelson, R. Riemann, B. Ruefenacht, D. Salajanu, D.L Weyermann, K.C. Winterberger, T.J. Brandeis, R.L. Czaplewski, R.E. McRoberts, P.L. Patterson, and R.P. Tymcio. 2008. Mapping U.S. forest biomass using nationwide forest inventory data and moderate resolution information. Remote Sensing of Environment 112: 1658-1677.

Bonfils, C., B.D. Santer, D.W. Pierce, H.G. Hidalgo, G. Bala, T. Das, T.P. Barnett, D.R. Cayan, C. Doutriaux, A.W. Wood, A. Mirin, and T. Nozawa. 2008. Detection and attribution of temperature changes in the mountainous western United States. Journal of Climate 21: 6404-6424.

Busing, R.T. and T. Fujimori. 2005. Biomass, production and woody detritus in an old coast redwood (Sequoia sempervirens) forest. Plant Ecology 177: 177-188.

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

Crimmins, S.M., S.Z. Dobrowski, J.A. Greenberg, J.T. Abatzoglou, and A.R. Mynsberge. 2011.

Changes in climatic water balance drive downhill shifts in plant species' optimum elevations. Science 331: 324-327.

Daly, C., D. Bachelet, J.M. Lenihan, R.P. Neilson, W. Parton, and D. Ojima. 2000. Dynamic simulation of tree–grass interactions for global change studies. Ecological Applications 10: 449-469.

Food and Agriculture Organization (FAO). 2001. Global forest resources assessment 2000. FAO, Rome, Italy.

Friedlingstein, P., R.A. Houghton, G. Marland, J. Hackler, T.A. Boden, T.J. Conway, J.G. Canadell, M.R. Raupach, P. Ciais, and C. Le Quéré. 2010. Update on CO_2 emissions. Nature Geoscience 3: 811-812.

Fry, J., G. Xian, S. Jin, J. Dewitz, C. Homer, L. Yang, C. Barnes, N. Herold, and J. Wickham. 2011. Completion of the 2006 National Land Cover Database for the conterminous United States. Photogrammetric Engineering and Remote Sensing 77: 858-864.

Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek. 2010. Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. Global Ecology and Biogeography 19: 755-768.

Intergovernmental Panel on Climate Change (IPCC). 2007a. Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC). 2007b. Climate Change 2007: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC). 2012. IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge University Press, Cambridge, UK.

Kuchler, A.W. 1964. Potential Natural Vegetation of the Conterminous United States. American Geographical Society, New York, NY.

Kunkel, K.E., L.E. Stevens, S.E. Stevens, E. Janssen, and K. Redmond. in review. Climate of the Southwest U.S. National Climate Assessment. U.S. Global Change Research Program, Washington, DC.

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling. 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. Ecological Applications 19: 1003-1021.

Marlon, J.R., P.J. Bartlein, D.G. Gavin, C.J. Long, R.S. Anderson, C.E. Briles, K.J. Brown, D. Colombaroli, D.J. Hallett, M.J. Power, E.A. Scharf, and M.K. Walsh. 2012. Long-term perspective on wildfires in the western USA. Proceedings of the National Academy of

Sciences of the USA 109: E535-E543.

Millar, C.I., R.D. Westfall, D.L. Delany, J.C. King, and L.J. Graumlich. 2004. Response of subalpine conifers in the Sierra Nevada, California, U.S.A., to 20th-Century warming and decadal climate variability. Arctic, Antarctic, and Alpine Research 36: 181-200.

Mitchell, T.D. and P.D. Jones. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25: 693-712.

Pierce, D.W., T.P., Barnett, H.G. Hidalgo. T. Das, C. Bonfils, B.D. Santer, G. Bala, M.D. Dettinger, D.R. Cayan, A. Mirin, A.W. Wood, and T. Nozawa. 2008. Attribution of declining western U.S. snowpack to human effects. Journal of Climate 21: 6425-6444.

Pounds, J.A., M.R. Bustamante, L.A. Coloma, J.A. Consuegra, M.P.L. Fogden, P.N. Foster, E. La Marca, K.L. Masters, A. Merino-Viteri, R. Puschendorf, S.R. Ron, G.A. Sanchez-Azofeifa, C.J. Still, and B.E. Young. 2006. Widespread amphibian extinctions from epidemic disease driven by global warming. Nature 439: 161-167.

Rosenzweig, C., D. Karoly, M. Vicarelli, P. Neofotis, Q. Wu, G. Casassa, A. Menzel, T.L. Root, N. Estrella, B. Seguin, P. Tryjanowski, C. Liu, S. Rawlins, and A. Imeson. 2008. Attributing physical and biological impacts to anthropogenic climate change. Nature 453: 353-357.

Stephenson, N.L. and A.J. Das. 2011. Comment on “Changes in climatic water balance drive downhill shifts in plant species’ optimum elevations.” Science 334: 177.

Swetnam, T.W. 1993. Fire history and climate change in giant sequoia groves. Science 262: 885–889.

Swetnam, T.W., C.H. Baisan, A.C. Caprio, P.M. Brown, R. Touchan, R.S. Anderson, and D.J. Hallett. 2009. Multi-millennial fire history of the Giant Forest, Sequoia National Park, California, USA. Fire Ecology 5: 120-150.

Tabor, K. and J.W. Williams. 2010. Globally downscaled climate projections for assessing the conservation impacts of climate change. Ecological Applications 20: 554-565.

Taylor, A.H. and A.E. Scholl. 2012. Climatic and human influences on fire regimes in mixed conifer forests in Yosemite National Park, USA. Forest Ecology and Management 267: 144-156.

Thorne, J.H., B.J. Morgan, and J.A. Kennedy. 2008. Vegetation change over sixty years in the central Sierra Nevada, California, USA. Madroño 55: 223-237.

Trouet, V., A.H. Taylor, E.R. Wahl, C.N. Skinner, and S.L. Stephens. 2010. Fire-climate interactions in the American West since 1400 CE. Geophysical Research Letters 37:

L04702. doi:10.1029/2009GL041695.

VEMAP Members. 1995. Vegetation/Ecosystem Modeling and Analysis Project (VEMAP): Comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO2 doubling. Global Biogeochemical Cycles 9: 407-437.

Westerling, A.L., B.P. Bryant, H.K. Preisler, T.P. Holmes, H.G. Hidalgo, T. Das, and S.R. Shrestha. 2011. Climate change and growth scenarios for California wildfire. Climatic Change 109: S445-S463.

Woodward, F.I., M.R. Lomas, and C.K. Kelly. 2004. Global climate and the distribution of plant biomes. Philosophical Transactions of the Royal Society of London B 359: 1465-1476.