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Climate Change; Confronting the Global Experiment

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Abstract

Earth's natural climate system is characterized by continually changing climates, with climate regimes that oscillate quasi-cyclically at multiple and nested scales from annual to multi-millennial, and commonly change abruptly. Under naturally changing climates, plant species track changes at all scales in individualistic manner, with plant communities changing as dominances fluctuate and species ranges shift. The capacity of plant species to adapt to changing natural climates depended historically on their ability to move over the landscape following favorable conditions. The human-dominated climate system, into which earth entered in the mid 20th century, extends beyond relevant historic reference in the nature of control (greenhouse gas emissions), rapid and global rates of directional change (warming), and super-elevated carbon dioxide and methane levels. Modeled future climates anticipate continuing trajectories of climate and greenhouse gases for several hundred years even if greenhouse gas emissions are reduced soon. The extensive human footprint of land use severely restricts the capacity of plant species to adapt to the rapid changes. General principles for vegetation management are elaborated under five "R's", and include: Reduce greenhouse gas emissions; Resist change; create Resilience to change; anticipate and enable Response to change; and conduct TRiage.

Introduction

Climate change is the primary currency of paleoecology, the study of past vegetation dynamics. Climate looms large because it is a key driver of historic vegetation change at multiple spatial and temporal scales, the force that sends species migrating up and down mountain ranges, expanding across basins, or contracting into fragmented populations. Large climate changes of the past have triggered speciation events and the evolution of major adaptations among and within species. Smaller climate changes have driven mixing and re-mixing of plant communities and catalyzed shifts in population size.

Paleoecologists and other scientists who study physical, ecological, and human aspects of the past are accustomed to documenting abrupt changes and regime shifts in the climate system, and equally rapid and complex responses in plant communities and ecosystems. In the past decade, however, paleoscientists have recognized that a new, human-dominated climate system has emerged, and that a global experiment of uncertain consequence is underway. Equally compelling is the recognition that, given the inertia of the climate system, the human influence on the current trajectory could not be reversed for decades to centuries. From the body of scientific literature that has emerged only recently, the 21st century appears destined to be the century of climate.

Given this, how can vegetation managers of private and public forest lands plan and respond intelligently? First is to recognize that solutions at the ground level, the managers' domain, do not yet exist. They will be wrought from collaborative discussion among colleagues – scientists, resource managers, planners, and the public – and they will be case-, location-, and project-specific. While general principles will emerge, the best preparation is for managers and planners to remain informed about the emerging climate science in their region, and to use that knowledge to shape effective local solutions. The goal of this paper is to engage that dialogue. In particular, I will briefly summarize natural climate patterns and mechanisms as important context for understanding current and future changes, provide an update on conditions of the human-dominated climate system, especially in California, and outline five general principles for vegetation management in the face of the ongoing global climate experiment.

The Natural Climate System

Changes in weather are familiar features of earth's surface, readily recognizable as diurnal variations, seasonal cycles, and annual differences that irregularly include extremes of drought, wet, heat, and cold. All forms of life are influenced by this variability in how and where they live, and mitigate adverse weather effects through conditioned responses and evolved adaptations. Until recently our knowledge of climate processes over longer time frames, however, was rudimentary. Understanding came mostly from interpreting indirect effects of climate on the earth's surface – e.g., glacial moraines as evidence of past ice ages, coastal terraces as clues to former sea levels – and these gave a view of slow change over time.

Climate Oscillates

In the past two decades, new tools with high precision and resolution, new theory reliant on high-speed computing capacity, and a critical mass of empirical research have revolutionized understanding of earth's climate system. Historic climate is now understood as being far more variable and complex than previously imagined (Bradley, 1999; Cronin, 1999; Ruddiman, 2001). Several key insights have emerged. First, climate naturally *changes* over time and the changes *cycle,* or *oscillate,* rather than wander stochastically or follow pervasive linear trends (Fig. 1). So, it is important when considering human-dominated climate change to recognize that change itself is natural and precedented, and to use this natural variability as a reference for evaluation. Because climate is cyclic, distant periods in the past may be more similar to the present than the immediate or recent past. Similarly, past variability may give better insight into the future than do current conditions. For instance, the 20th century and especially the middle of the 20th century (when many of us grew up) were the least variable and wettest decades in the past 1000 years (Graumlich 1993), and thus may inform us poorly about future variability and drought. Importantly, although average regimes cycle (e.g., cold:warm, wet:dry), exact climates (combinations of variables) are expressed uniquely over time, and historic patterns are not blueprints for future iterations.

Climate Cycles at Multiple Scales

A second major insight is that climate has varied simultaneously at *multiple and nested scales*, operating at multi-millennial, millennial, century, decadal, and interannual scales (Fig. 1), and caused by independent physical mechanisms. Major interglacial and glacial periods cycle on multi-millennial scales. These drive temperature changes on the order of 10-15°C, and are caused by oscillating changes in the pattern of earth's orbit around the sun. At the century scale, recurring variations in the sun's activity drive cycles of about 1200-year periodicities. The Medieval Warm Period (900-1300 CE [common era]) and Little Ice Age (1450-1900 CE) are expressions, respectively, of warm and cool phases of this multi-century scale climate mode. The now familiar El-Niño/La Niña cycle (called ENSO, for El-Niño Southern Oscillation) is an example of an interannual climate mode, and a similar 30-40 year oscillator, the Pacific Decadal Oscillation, affects the west coast of North America. These shorter cycles result from mechanisms internal to earth, that is, the recycling patterns of ocean circulation and ocean temperature. The separate mechanisms of these various cycles interact and feedback to one another, creating gradual as well as abrupt changes. Climate at any one time is the cumulative expression of all mechanisms operating together.

Climate Often Changes Abruptly

Third, paleoclimate science informs us that transitions between major as well as minor climate phases often occur *abruptly* (a few years to decades), and can be accompanied by significant changes in climate regime. Climate states are highly sensitive, catalyzed by threshold and feedback events, triggered by stochastic effects, and especially vulnerable during times of high variability such as the present (NRC, 2002). For example, although glacial/interglacial periods are long, changes between states can be abrupt. The transition from cold to warm at the end of the last glacial period went through a series of 1000-year reversals, or flickering switches, before settling into our warm interglacial. Annual temperature change was studied over 150 years during the end of the Younger Dryas, one of these 1000-year reversals. A total of 15°C warming occurred in two 10-year periods (ca. 7-8°C each) separated by a 20-

year plateau of no detectable change (White et al., 2001). A recent example at a different scale is the western North America regime shift at 1975-1976. Abrupt, coincidental changes in the climate of the previous two decades occurred in many variables, including temperature, precipitation, air temperature, snowpack, and ocean temperature to conditions that have characterized western U.S. since the mid 1970s (Ebbesmeyer, et al., 1991).

Vegetation Responds Complexly to Climate Change

Finally, *ecological and physical systems respond to climate change* at each scale. Temperature and precipitation directly affect water availability in the form of rain, snow, ice, and glacier, and cascade to changes in streamflow, groundwater and aquifers, soil moisture, and erosion. Plants and animals react to climate and changes in the hydrologic system with shifts, often dramatic, in population size, range distributions, and community compositions and dominances. These are often accompanied by changes in fire regimes and insect/pathogen relations.

Millennial Time Scale. At long time scales (glacial to interglacial), records collectively document that, at any one place, compositions of flora change significantly in correspondence with major climate phases, often showing complete species turnover and recurring patterns of similar groups of species or species with similar adaptations alternating between glacial and interglacial periods. In relatively flat terrain, such as in northeastern United States, eastern Canada, parts of Scandinavia, and northern Asia, species shifted latitudinally north and south several thousand kilometers over 4,000 years at the end of the last ice age, as modeled, for example, for spruce (*Picea*) in eastern North America (Jackson et al., 1987). In mountainous regions, by contrast, species respond primarily by elevational shifts of 1500 m or more (Thompson, 1990). An example is giant sequoia (*Sequoiadendron giganteum*). Currently limited to small and disjunct groves between 1500-2100 m in the southwestern Sierra Nevada, giant sequoia’s range over the past 10,000-26,000 years included the eastern Sierra Nevada (Mono Lake, Davis, 1999a), and locations in the western Sierra Nevada that are both well above (2863 m; Power, 1998) and below (1000 m in current chaparral shrubland, Cole, 1983; and 54m at Tulare Lake in the California Central Valley, Davis, 1999b) its current range. Giant sequoia did not appear in its current range in Sequoia National Park until 4500 years ago, and did not reach modern abundance there until about 2000 years ago, i.e., approximately the age of the oldest living individuals (Anderson and Smith, 1994). Thus, giant sequoia has not been in its present distribution in the Giant Forest area longer than about a single generation.

Century Time Scales. Shifts in plant elevation and distribution ranges have occurred in California over century scales, including recent times. These changes are similar in nature but smaller in magnitude than range shifts and community changes at glacial/interglacial scale. For example, large dead tree stems preserved in cold, arid conditions above current treeline in the eastern Sierra Nevada date to the warm Medieval period, 650 to 1100 years ago. They were identified from wood anatomy to include species whose current upper range limits are 200-800 m below the site (Fig. 2; Millar, et al., in press). This mixed-conifer forest included six species that don't currently occur together. Especially unusual is the presence of large stems of sugar pine (*Pinus lambertiana*), a species not currently native to the eastern Sierra, but which grows at mid-elevations in mesic, westslope, forest conditions.

Interannual and Decadal Time Scales. At interannual ENSO scales, changes occur primarily in plant productivity and abundance within populations. The oscillations contribute to regional fire regimes, where fuel loads build during wet years and burn during dry years. These lead to meso-scale vegetation changes as ENSO itself cycles, and thus fire regimes change over time (Swetnam and Betancourt, 1998; Kitzberger et al., 2001). Longer term, decadal-scale vegetation oscillations have been well documented in secondary growth of trees, such as recurring multi-year droughts over the past 400 years that led to reduced ring-widths in ponderosa pine in New Mexico (Grissino-Mayer, 1996), and the recurring pattern of ring-widths in conifers of the west (Biondi et al., 2001; Peterson and Peterson, 2001; Gray et al., 2003) that correlate with multidecadal phases of the Pacific Decadal Oscillation (PDO). Vegetation type conversions from meadow to forest, changes in species growth rates and crown morphology, and changes in forest density are also associated with 20th-century PDO cycles in conifer forests of the Sierra Nevada (Millar et al., 2004). Shifts in treeline, movement of forests among aspects, and changes in extent of mountain meadows are other examples of changes at this scale.

The Human–Dominated Climate System

Given the dynamics of the natural climate system in the past, it is not surprising that climate would be changing now as well. Considering the past 1000 years, the amplitude of natural temperature cycles has been about +/-1°C from the average of the mid-20th century – warmer by this amount during the Medieval centuries and colder during the Little Ice Age. The natural mechanisms that led to the Little Ice Age reversed in the late 1800s, and by 1900, temperatures again began warming. So where does human influence on the climate system and global warming enter?

The Global Perspective

In 1998, the World Meteorological Organization and the United Nations Environment Programme formed the Intergovernmental Panel on Climate Change (IPCC). The role of the IPCC is to assess on a comprehensive, objective, open, and transparent basis the scientific, technical and socio-economic information relevant to understanding the risk of human-induced climate change, its potential impacts and options for adaptation and mitigation. The IPCC's Scientific Assessment Reports, issued in 1990, 1995, 2001, and Fourth anticipated for 2007, are widely accepted as representing a synthesis of the world's scientific consensus on recent climate change.

A key question the IPCC addresses is: *How has global temperature changed over the last 100 years, and how has this compared to the past 1000 years?* Answers to the first question came from compilations of instrumental data across earth's surface and indicate a temperature increase of ~ 0.7°C over the 20th century (IPCC, 2001; Fig. 3). Temperature increase relative to the past 1000 years has resulted in a number of interpretations depending on the nature of the proxy (climate indicator, such as tree rings, corals, ice cores, etc.) and the statistical interpretation. The global average temperature in the late 20th century was higher than global averages over the last 1000 years although some regions experienced significantly warmer conditions. Regardless of relative change in the earlier centuries, the trend of increasing temperature late in the 20th century is clear in all interpretations.

Another key question for the IPCC analyses is: *Are globally observed 20th-century warming trends the result of natural processes or human influences via greenhouse gas emissions?* This question is now answered with high confidence: the trends in global climate since about 1975 can only be explained by non-natural forces. Without human influence, the models indicate that the natural climate systems would be cooling slightly, as a result of solar activity and atmospheric dimming from volcanic aerosols. The observed warming trends are duplicated in models only when anthropogenic greenhouse gas (GHG) emissions (carbon dioxide [CO_2], methane [CH_3], and others), and their feedback effects, are added to the models (IPCC, 2001).

The IPCC also has been charged to generate models of future climates, called scenarios, which rely on an increasing array of General Circulation Models. Diverse models are used to generate a range of results that derive from different process approaches, as well as starting assumptions. These include, for instance, different emissions conditions, such as "Business as Usual" (no change from current practices), doubled, and tripled CO_2 levels. The ensemble of scenarios depicts a global average temperature increase of 1.5 – 5.8°C by 2100 (Fig. 4) and a range in CO_2 concentrations of 575-1000 ppm. Considering the extreme values in these ranges, the last time global temperature was this warm was during the last interglacial period, about 120,000 years ago, and the last time CO_2 concentrations were this high was about 120 million years ago when earth was in a radically different atmospheric, tectonic, and environmental condition than present (Berner, 1990).

Elevated levels of atmospheric CO_2 have direct effects on ecosystems in addition to influencing climate. Some of these are likely to be detrimental, such as acidification of oceans, with cascading effects to ocean biota. The role of increased efficiency of photosynthesis by plants has been touted as beneficial for the fertilizing effect on tree growth. Increasingly, studies show this is not a universal effect, and that the additional photosynthate is not always stored in wood nor does it necessarily result in accelerated growth. Depending on species, age, and time since exposure, CO_2 may be stored in stems, roots, or fruits. Old-growth forests respond less than young trees, and also show a capacity to acclimate to the high levels of CO_2 such that growth increases initially, then declines (Körner et al., 2005).

Cascading environmental effects from a continually warming world are already widely documented and projected to accelerate. These include decreased arctic ice cover (down 23% since first monitored in 1979); increasing sea level as sea ice and ice caps melt (CCSP, 2005); changes in earth surface albedo as bare ground is exposed in the Arctic, and especially as shrubs invade (Chapin et al., 2005); worldwide retreat of mountain glaciers and ice caps (averaging ~50% decline over western U.S. during the 20th century; Mennis and Fountain, 2001); advancing spring and concomitant changes in plant phenology (Cayan et al., 2001); decreased snowpack accumulation and associated decreases in streamflow (Dettinger and Cayan, 1995); increases in amplitude of extreme weather events (hurricanes, drought, flood; CCSP, 2005); "greening up" of temperate lowland and montane forests (i.e., increases in density) followed by "browning down" (mortality) as a result of epic forest dieback (stress + insects, disease) and uncharacteristically severe wildfire (Westerling et al., 2003; Breshears et al., 2005); and loss of alpine ecosystems as high-elevations species move upward off the tops of peaks (Pauli et al., 2003).

An important take-home message from the IPCC analyses is the inertia of the climate system. Assuming GHG emissions peak and could be restored to early 20th-century levels within the next 50 years, the residence time of CO_2 in the atmosphere is such that it would not stabilize for 100-300 years and temperature would not stabilize for the same amount of time (IPCC, 2001). Thus, the scenarios for the 21st century show best-case assumptions for GHG emissions; if GHG are not controlled, climate changes will be significantly amplified. The effects of anthropogenic GHG emissions on climate combined with land-use changes that affect climate are what give rise to recognizing the human-dominated climate system as characteristic of the new millennium.

Climate and Ecosystem Trends in California and the West

The trend of temperature change for the western United States has paralleled the global pattern with regional variability. From 1966 to 2005, temperatures in the western states increased about 0.8°C (Redmond, 2004), and in some mountainous areas by as much as 1.5-2°C (WRCC, 2005; Millar et al., 2004). On average, precipitation has not shown strong directional changes, rather it is highly variable. Shorter term annual and interannual influences of ENSO and PDO strongly affect the Pacific states. Whereas multi-year (3-8 year) droughts have been equally or more common in past centuries (NOAA, 2005), interaction of drought with increased temperature results in greater stress to vegetation than under cooler climates.

Changes in snowpack amount and water availability will be the most significant and widespread effect of climate changes in the West. Decreases in snowpack up to 80% between 1950-1997 were documented throughout most of the west, although central and southern Sierra Nevada are anomalous (Hamlet et al., 2005; Mote et al., 2005). During the same period, throughout most of the west, snowpacks peaked earlier in winter, by as much as 45 days in some areas, although again the southern Sierra snowpacks peaked slightly later (Hamlet, et al., 2005). These trends cascade to changes in timing of streamflow, and extent of summer water reserved, as much as 20% increase in March mountain streamflow and decreases up to 20% in April (Stewart et al., 2005). The combined effects portend longer summer droughts, and declining soil moisture availability during the growing season, especially as temperatures increase, adding to the stress of California's Mediterranean summer on plants.

Effects on forest vegetation are increasing as temperature increases, water availability decreases, and multi-year droughts punctuate background trends. The recent 2000-2004 drought of the West contributed to epic levels of forest mortality on the Colorado plateau (Breshears et al, 2005), southern California (FRAP, 2004), and the Pacific Northwest and Intermountain region (Logan and Powell, 2004). Similarly, the annual areal extent of forests burned in wildfires has increased, as a combined effect of 20th-century temperature increases, variability in precipitation, and land-use changes (Fig. 5, Westerling, 2005.). Complex changes in upper montane and subalpine forests (Millar et al., 2004) and shifts of wildlife species distributions upslope (MVZ, 2005) are attributed to 20th-century climate.

Many of the climate and ecological trends documented for the 20th century are projected to continue and exacerbate in the 21st century. Future climate scenarios and effects on water, forests, fires, insects and disease are summarized in Hayhoe et al., (2004; Fig. 6) and the annual report of the California Climate Action Team (CCAT, 2005). These projections result from regional downscaling of global models, and display a range of results for conditions through the 21st century. All models show increased temperatures over California, with results ranging from 2.3-5.8°C annual temperature increase. Most models show elevated warming for central eastern and northern California relative to the rest of the state (Hayhoe, et al., 2004). While prior modeling efforts indicated slightly wetter conditions in California's future, current models mostly indicate drying. Variability in results is large, however, and estimates of annual precipitation range from a decrease of 157 mm to an increase of 38 mm. Snowpacks are consistently modeled as declining by as much as 97% at 1000 m elevation and 89% for all elevations.

Coupling climate models with vegetation models yields major contractions and expansions in cover of dominant vegetation types by the late 21st century (Hayhoe et al., 2004; Fig. 7). By 2070-2099, alpine and subalpine forest types are modeled to decline by up to 90%, shrublands by 75%, and mixed evergreen woodland by 50%. In contrast, mixed evergreen forest and grasslands are each modeled to expand by almost 100%. Similar shifts were modeled by Lenihan et al. (2005). For midslope westside Sierra Nevada forests, Battles et al. (2005) projected declines in conifer tree growth during the 21st century under all climate models. In the extreme climate scenario, productivity in mature stands was reduced by 18% by the end of the century. In pine plantations, typical of those used in forest industry, reductions in yield were more severe, up to 31%.

Fire modeling for this period reflected differences in response during the 21st century depending on vegetation type (Westerling and Bryant, 2005; Lenihan et al. 2005). Overall in California, increased temperatures and slightly declining precipitation resulted in 12-53% increase in risk of large (>200 ha) wildfires and up to 15% in all fires by the end of the century (Cayan et al., 2005). The model results, however, showed opposite effects for energy-limited versus fuel-limited fire-vegetation regimes and these changed over the 21st century as vegetation types replaced one another. In areas where fuel loads remain high, such as the west slope Sierran forests, increasing temperatures create higher fuel loads with concomittant increases in fire risk up to 90% (Westerling and Bryant, 2005). By contrast, in areas such as southern California and the coastal shrublands, where fuels limit fire risk and spread, decreases as much as 29% are modeled. As grasslands and other low-fuels vegetation types replace forests in areas that have burned over the century, fire risk would decline.

Notwithstanding the complexity of host-pathogen relations, moderate increases in risk of non-fire causes of tree mortality (i.e., insects and pathogens) were modeled under most climate scenarios in vulnerable species (Battles et al., 2005). For example, as a result of diverse biotic stresses, survival probabilities in white fir (*Abies concolor*) declined from the background of 0.997/yr to 0.982/yr in westslope central Sierra Nevada forests by 2099. More difficult to model are the interactions of climate change with invasive species that may lead to surprising and abrupt effects, such as the recent expansion of pitch canker from the California coast range into Sierran conifer forests. A promising approach is to use physiologically based models to project changes in areas of favorability for pathogens under different climate scenarios. This was done for the Cotton/Pink Bollworm, a pest of cotton production currently limited by frost restrictions to the desert regions of southern California. Warmer climates are projected to enable the bollworm to expand extensively northward into other important agricultural areas in California (Gutierrez, 2005).

Vegetation Management in the Face of Changing Climates

Given this climate context, what can forest managers do to plan and respond intelligently? While solutions depend on specific situations, general guidelines apply. These can be categorized as *mitigation*, *adaptation*, and *conservation*. Mitigation practices aim to reduce emissions of new GHGs, as well as to remove existing CO_2 from the atmosphere. Adaptation practices include actions to increase the capacity of ecosystems and society to function productively under changing climates and greenhouse atmospheres. Conservation practices include all those actions that reduce energy use and dependence on fossil-fuels, and thereby relieve stress on ecosystems and ecosystem services. For resource management to meet these three principles, I outline the “Five R” strategies. They are *Reduce* GHGs, *Resist* Change, *Resile* After Disturbance, *Respond* to Change, and Conduct *TRiage*. While these guidelines pertain to many situations, the discussion here addresses production forest management on private and public lands. For similar discussion specific to restoration ecology, conservation practices, and lands managed primarily for biodiversity, see Millar and Brubaker, 2006; Millar, 2004; and Millar and Woolfenden, 1999.

Reduce *Greenhouse Gases*

To date, discussion in western forestry and land-management circles regarding climate has focused on adaptation to anticipated changes. A priority, however, must be to contribute actively to mitigation of anthropogenic climate and atmospheric effects by reducing GHG emissions. The forestry sector is especially called to action because the potential for positive effects through deliberate forest management is large, and, conversely, there is great potential for negative impacts when forests are mis-managed or carbon issues ignored. While the U.S. has fallen far behind other countries in developing stringent federal standards and emissions caps, many U.S. states including California have established their own standards that compare to Kyoto-protocol countries. On 1 June 2005, Governor Schwarzenegger signed Executive Order # S-3-05, which established the following GHG targets for the state:

- By 2010, Reduce to 2000 Emission Levels
- By 2020, Reduce to 1990 Emission Levels
- By 2050, Reduce to 80 percent Below 1990 Levels

To meet the targets, the Governor directed California Environmental Protection Agency to coordinate approaches with the Business, Transportation and Housing Agency, Department of Food and Agriculture, Resources Agency, Air Resources Board, Energy Commission, and Public Utilities Commission. The Secretary of CalEPA leads the California Climate Action Team, which implements global-warming emission-reduction programs, and reports progress made toward meeting the statewide GHG targets. The first report (draft) to the Governor and the Legislature was delivered in December 2005, and contains valuable scientific information on state-of-the-art models, impact assessments, and mitigation/adaptation strategies (CCAT, 2005).

Sequester GHG. Plants and especially long-lived trees are excellent factories for removing CO_2 from the atmosphere. Plants remove CO_2 during the process of photosynthesis, and, with water, convert carbon to wood and other plant parts. Under natural conditions carbon is stored in plant parts above- and belowground until it is returned to the atmosphere via burning (combustion) or decomposition, or further stored in the soil. Carbon is stored, or sequestered, in live plant tissues as stems, leaves, and roots, in dead tissue as stems and litter, and in soil pools in diverse forms. The amount of CO_2 taken in varies over the life of a tree and a forest stand. In a typical California conifer forest, at about 100 years, 70% of the carbon is stored in aboveground biomass, 10% each in litter and belowground biomass, and the rest in dead stems and other plant parts (Kadyszewski et al., 2005). Over 99% of the carbon sequestered in a forest is by trees. A 150-year-old Sierra mixed-conifer forest sequesters 575 CO_2 tons/ac; a similar aged redwood forest, 730 CO_2 tons/ac (Kadyszewski et al., 2005). Carbon in plant tissues is further sequestered when fibers are used as timber (construction, etc.) or other forest products. From the climate/greenhouse standpoint, benefits are accrued the longer carbon is bound up in plant form (live trees, litter, soil, wood and fiber products) and not returned to the atmosphere.

Forest management practices designed to achieve goals of removing and storing CO_2 are diverse. A recent study on carbon sequestration options identified that “afforestation provides the biggest terrestrial sequestration opportunity in California, Oregon, and Washington” (Kadyszewski et al., 2005). Afforestation involves converting non-forest land into forested condition, either restoring native forests (e.g., forest that had been cleared) or establishing plantations on land that was not previously forested. Marginal agricultural lands and grazing lands are prime candidates for afforestation, and as many as 24 million acres of California rangeland and grasslands have potential (soil, water-capacity, climate) to support forests if planted and managed (USC, 2005).

Other approaches to sequestering carbon duplicate long-recognized best forest management practices where the goals are to maintain healthy, vigorous growing stock, keep sites fully occupied with minimal spatial or temporal gaps in non-forest conditions, and minimize disturbance by fire, insects, and disease. Responsible sequestration practices delay return of CO_2 to the atmosphere, both in situ (in the forest or plantation) and post-harvest. The following practices are suggestive of actions that favor carbon sequestration in forests and plantations:

• Reforest after harvest or disturbance, and maintain forest cover with minimal gaps in time and space;
• Resist site conversion to non-forest types;
• Use mixed species, genotypes, and age classes to fully utilize the site;
• Plant with broadly adapted and fast-growing species, using generally adapted genotypes;
• Thin to improve growth but keep sites fully occupied;
• To minimize erosion and soil/litter disturbance, limit number of entries;
• Extend rotation lengths – as few as five extra years adds considerably to carbon pooling;
• Protect forests and plantations from fire and insect/disease; if reducing fuels, use thinning practices rather than managed fire unless the latter is essential for nutrient improvement or biodiversity protection;
• Widen riparian zones;
• Restore and maintain old forests, especially those with high structural diversity and low fire vulnerability.

Once fiber is removed from the forest or plantation, its path through the utilization cycle continues to affect its carbon emissions status. Options include storing carbon in wood and fiber form as buildings, paper, fiberboard, etc., or used for biomass to fuel electricity production. The latter provides a tremendous opportunity for the future, as wood removed from the forest not only reduces GHG emissions by reducing fire vulnerabilities but provides alternative energy to replace fossil-fuel and other high GHG-emitting forms of energy. A model example comes from a new program on the Fremont National Forest near Lakeview, OR, the Lakeview Biomass Project. The project plans to build a new electrical production plant fueled by biomass and sawmill byproducts derived from thinning overdense stands on the Fremont National Forest. A sustainable supply of wood from small trees with little market value otherwise exists on these public forestlands. The cost of building the new power plant would be offset with the sale of electricity and steam from the plant, as well as sawlogs from the same forestland. A major incentive for the project is to reduce GHG emissions through reducing wildfire risk and supplying alternative energy sources. In 2005 the Lakeview Biomass Project was endorsed by Oregon's governor as a formal "Oregon Solutions" project, assuring priority and commitment from state agencies and funding. In California, co-generation plants have been in and out of operation for over 20 years, with most success in eastside pine regions of NE California (Fig. 9). Without economic or carbon trading incentives and with limited public acceptance for harvest, these have been economically difficult to maintain despite advantages from a carbon perspective.

In the best of circumstances, CO_2 gas would be separated during combustion and further sequestered, delaying the return of GHG to the atmosphere. While isolation is now technologically possible, it is not yet operational in forestry situations. Nonetheless, capacity is being developed for geologic sequestration, that is, injecting CO_2 gas into suitable longterm underground storage layers. Geologic sequestration is proving to be safe, and large capacities are available. Options for storage include depleted oil and gas reservoirs, deep saline strata, deep unmineable coal seams, oil shales, basalts, and cavities. Many lines of evidence indicate that this approach can be secure and effective, as has been proven in other situations, such as the Sleipner project in the North Sea, where 1Mt CO_2 / yr have been sequestered in strata more than 1000 m below the seafloor since 1996 (Benson, 2005). In California, options exist for storage in depleted oil and gas reservoirs, and deep saline formations that are widespread below the Central Valley. In a capability screening study of California, 121 fields met standards for safety, depth, and capacity, and pilot tests are underway in four sites (Benson, 2005).

Reduce Unnecessary Emissions. Wildfire is a primary source of unintentional carbon emissions from forests in western U.S., and represents catastrophic loss of decades to centuries worth of carbon storage. This situation is likely to be worsening, in the near term at least, in that forest growth has increased during the 20th century due to warming and wetter climates as well as decades of fire suppression ("green-up"), priming overdense stands for wildfire during dry years and droughty periods (Lenihan et al., 2005; Westerling and Bryant, 2005; Westerling et al., 2003). The 2002-2003 fire season in western North America was an example. Forest losses during the 2002 wildfire season in Colorado, for example, reversed years of carbon uptake. The amount of carbon dioxide released from trees during the fires equaled an entire year's emissions from statewide transportation activities (David Schimel, NCAR, pers. comm. 2005). In 2003, almost 800,000 acres of forests and chaparral burned in California (USC, 2005). This effect will exacerbate in coming decades under continued warming, with increasing catastrophic fire years leading to what has been modeled as widespread “brown-downs” for many western and eastern forest types (Ron Neilson, USFS, pers. comm., 2005).

Similarly, extensive forest mortality as a result of overdense, stressed forests vulnerable to insect and disease outbreaks also leads to large pulses of carbon release through decomposition. For example, the extensive forest dieback triggered by drought centered on 1999 – 2004 in western North America will rapidly become a significant source of carbon emissions. Associated watershed erosion and soil disturbance will increase the emissions impact. In such cases, notwithstanding other concerns, salvage harvest of dead trees would be desired.

Management practices that lower forest vulnerabilities to wildfire and non-fire mortality must be widely implemented. On public forest lands, while there is support for fuel and fire reduction, there has been public pressure to minimize harvest (thinning) and to use managed fires instead. While this may be important for ecological values, from a carbon-accounting standpoint it is less desirable. Removing trees (thinning or chipping) from dense or dead stands is appropriate where this practice lessens fire risk, and especially if the fiber is subsequently used as biomass to fuel energy co-generation or stored longterm.

Maintain House in Order. While not directly related to vegetation management, energy conservation and reduction of emissions from resource-related activities should be a priority for forestry and environmental institutions. Vehicles are the single largest source of CO_2 emissions in California, accounting for 41% of the total, with industrial production in second place at 22% and electricity 20% (Bemis and Allen, 2005). Instituting incentives for employees to reduce travel, encourage hybrid vehicles and public transportation, and carpool should be base standards. Based on a 2005 Presidential Memorandum, the Chief of the U.S. Forest Service issued a directive on energy and fuel conservation that requires 10% agency-wide reductions in energy use, travel, and use of gas-fueled vehicles. He further proposed changes in agency fleets to include hybrid and other clean-fueled transportation, and outlined employee incentives to telecommute, use public transportation, etc. (Bosworth, 2005). Many state and utility programs offer rebates and incentives to install solar panels, wind-generators, and to reduce gas and electricity usage. Energy audits are readily performed and many types of carbon calculators are available online. Green tag programs, such as that run by the Bonneville Environmental Foundation, encourage trading of energy debt (paid by individuals to offset GHG emissions) to entities that provide clean energy sources. Many other businesses and organizations (e.g., Carbon Neutral Company, TerraPass) have been developed with missions to mitigate climate effects by promoting positive and practical actions to reduce emissions.

As part of California's commitment, the Climate Action Registry was established by California statute as a non-profit voluntary registry for GHG emissions. The purpose of the Registry is to help companies and organizations with operations in the state to establish GHG baselines against which any future GHG emission reduction requirements may be applied. The Registry encourages voluntary actions to increase energy efficiency and decrease GHG emissions. Using any year from 1990 forward as base year, participants can record their GHG emissions in the Registry's inventory using an online calculator. As such, participants become "certified", and the state of California in turn offers its best efforts to ensure that participants receive appropriate consideration for early actions in the event of future state, federal or international GHG regulatory scheme. Registry participants include businesses, non-profit organizations, municipalities, state agencies, and others.

***Resist** Effects of Climate Change*

On the adaptation side of management options, one approach is to resist the influence of climate change on forest resources. From high-value plantation investments near rotation to rare species with limited available habitat, maintaining the status quo may be the only option. In California, this will almost always involve protecting resources from fire, insect, and disease. Options include traditional fuel breaks, strategically placed area treatments, defensible fuel profile zones, group selection, and individual tree removal. Intensive and complete fuel breaks may be necessary around highest risk areas, such as wildland-urban interfaces and valuable plantations, while mixed approaches may best protect habitat for biodiversity.

Abrupt invasions, changes in behavior, and long-distance movements of non-native species are expected in response to changing climates. Monitoring non-native species and taking early actions to remove and block invasions is important. This applies to invasive plants, animals (vertebrate and invertebrates), and pathogens. Movement of pitch canker into westslope Sierra Nevada forests is an example. Other pathogens, such as white pine blister rust (*Cronartium ribicola*) historically expanded during "wave years" that relate to weather events (e.g., severe El Niño events), suggesting that changing climates may advantage these species in unexpected ways. Aggressive early resistance is critical.

Resisting climate change influences on natural forests and vegetation may require additional investments, intensive management, and a recognition that one is "paddling upstream" against nature. For instance, climate change in some places will drive site conversion so that site capacities shift from favoring one species to another. Maintaining prior species may require significant extra and repeated efforts to supply needed nutrients and water, remove competing understory, fertilize young plantations, develop a cover species, thin, and prune.

An example from the Pacific Northwest exemplifies the potential problem. Mountain pine beetle (*Dendroctonus ponderosae*) is a native species on pines of western North America, in particular lodgepole pine. Cold conditions at high latitudes along the Rocky Mountains in eastern British Columbia historically maintained mountain pine beetle's range west of the continental divide. During the late 20th century, warming temperatures, combined with drought-weakened pines during the late 1990s, created conditions where massive beetle outbreaks spread beyond their historic limits. In 2003 outbreaks occurred for the first time east of the continental divide. These are only 50 km from native populations of jack pine (*Pinus banksiana*), another host for the beetle. This event is of concern for potential leapfrog impacts. Should mountain pine beetle populations expand eastward across Canada through jack pine forests, they would encounter a continuous string of potential host species along the eastern seaboard of the U.S., and might eventually spread to the industrial pine belts of southeast U.S. (Logan and Powell, 2004). There infestation would have serious economic impact. This is a situation where resisting change through aggressive control of colonizing insect populations east of the continental divide in B.C. would be warranted.

Create ***Resilient*** *Vegetation*

Resilient forests and plantations are those that not only resist change but resile (*verb*: to return to a prior condition) after disturbance. Resiliency of vegetation can be increased by management practices similar to those described for resisting change. These include practices to reduce fire risk, and also aggressive actions to encourage return of the site to desired species post-disturbance. Given that the plant establishment phase tends to be most sensitive to climate-induced changes in site potential, intensive management at young ages may enable retention of the site by a commercially desired species, even if the site is no longer optimal for it. Practices include intensive site preparation, replanting with high-quality stock, diligent stand improvement practices, and minimizing invasion by non-native species.

Unfortunately many examples are accumulating where resilience is declining in natural forests. One case is the Colorado Plateau, where recent drought led to massive mortality in pinyon and ponderosa pine forests. Much of the former forest area is converting to grasslands, an effect that appears related to changing climates and exacerbated by land-use effects (Breshears et al., 2005). Vegetation projections for California suggest that much forest land will convert to non-forest grass-, shrub-, and woodland (Hayhoe et al., 2004; Lenihan et al. 2005). Retaining resiliency will become more difficult as changes in climate accelerate.

Respond *to Climate Change*

A fourth adaptation option for management is to anticipate the effects of projected future climate on vegetation and plan protective and opportunistic measures in response. For this to be useful requires that climate and response models yield useful projections. While regional modeling is becoming increasingly sophisticated, outcomes should be considered highly uncertain at the local spatial and temporal scales used in forest management. This is partly because large uncertainties exist at global climate scales that translate and amplify as models are downscaled to regional levels. Rather than viewing models as forecasts or predictions of the future, they are better used for attaining insight into the nature of potential process and about generalized trends. Focusing on results that are similar across diverse models should indicate areas of greater likelihood. Ecological response (including fire and insect/disease) to climate is even more difficult than climate to model accurately at local scales because threshold and non-linear responses, lags and reversals, individualistic behaviors, and stochastic and catastrophic events are common. Models typically rely on directional shifts following equilibrium dynamics of entire plant communities, whereas especially in mountainous regions, patchy environments increase the likelihood of complex individualistic responses. The paleoecological record can be useful for interpreting complex responses of vegetation to climate (e.g., Millar 1999, Millar et al., 2004, 2006).

Once a forest manager obtains regional information about future climate scenarios, either from sophisticated modeling or qualitative extrapolations, options for managing resources in response to anticipated change can be developed. Depending on management goals and the environmental context, different approaches may be taken. A sample of these includes the following:

Follow Climate Change. As climate changes, habitat for species (or "niche space") shifts in response. Models project movement of broad vegetation types given specific scenarios of climate change and give a general idea of where habitat might shift, expand, or contract. Models that project movement of niche space for individual species are just being developed and not yet available for many species. These are helpful in that they give managers insight into whether their managed stands or plantations are likely to remain within a species niche space or not, and how conditions will change within current stands and plantations as well as the adjacent landscape. With such information, managers might modify rotation lengths and harvest schedules, alter thinning prescriptions and other silvicultural treatments, consider replanting with different species, shift desired species to new plantation or forest locations, or take precautions to mitigate likely increases in stress on plantation and forest trees.

While it has a become a common assumption that species and communities will shift uphill to find favorable sites as climates warm, and similarly that moving managed plantations uphill is the appropriate response, it is important not to generalize assumptions about habitat and climate in specific areas. Local climate trajectories may be far different than state or regional trends, and local topography and microclimatology interact in ways that may yield very different climate conditions than those given by broad-scale models. In mountainous terrain especially, the climate landscape is patchy and highly variable, with local inversions, wind patterns, aspect differences, soil relations, storm tracks, and hydrology influencing weather that a site experiences. Sometimes lower elevations may be refugial during warming conditions, as in inversion-prone basins, deep and narrow canyons, riparian zones, and north slopes. Such patterns, and occupation of them by plants during transitional climate periods, are corroborated in the paleoecological record.

Despite the challenges in mountainous terrain, anticipating where climate and local species spaces will move will become increasingly important. On-the-ground monitoring of native species gives insight into what plants themselves are experiencing, and can suggest the directions of change and appropriate natural response at local scales. This can allow management strategies that mimic ("go with the flow") natural responses. For instance, new species mixes (mimicking what is regenerating naturally or growing better than plantation species), different genotype selections, modified age structures, and altered silvicultural contexts (e.g., selection harvest versus clearcut) may be suggested.

Anticipate & Plan for Indirect Effects.   Risks of wildfire, insect and disease, and invasive species change as climate changes. Just as niche space for desired species moves, so will niche space for undesired species and environmental conditions, often greatly altering areas of interaction, as described for the cotton pink bollworm and pitch canker in California and mountain pine beetle in British Columbia. Striking examples of this are now being described with non-forest native species, where climate changes catalyzed previously innocuous native disease organisms to epidemic levels (e.g., amphibia, Pounds et al., 2006; salt marshes, Silliman et al., 2005).

Increase Redundancy. While some situations may implicate "putting your eggs in one basket" and trusting that climate and vegetation models accurately project the future, for other situations, hedge-betting practices may be a better choice. Essentially this group of actions plans for uncertainty in the future rather than a certain (modeled) scenario. This further assumes that accuracy of future scenarios is low, but that there is high probability that the future brings change and also greater variability (El Niño, multi-year droughts, extreme weather events, etc.). Actions in this category are taken that spread risk rather than concentrating it, such as increasing redundancy of plantations and managed forest stands over wider ranges of environments than previously used – favoring diverse environments and even species margins. Planting with mixed species and age classes within plantations and stands also increases likelihood of maintaining growth and productivity against an uncertain future. A benefit of redundant plantings across a range of environments is that these can provide monitoring information if survival and performance are measured and analyzed. In the same way, monitoring opportunistically, such as horticultural plantings of native species in landscaping, gardens, or parks may give clues on how species respond in different sites as climate changes.

Expand Genetic Diversity Guidelines. While in the past several decades, genetic guidelines for reforestation have been increasingly refined to favor local germplasm and close adaptation, relaxing these guidelines may be appropriate under changing climates as another hedge-betting practice. While "local" remains important, planting stock choices may be expanded to include a proportion of germplasm from adjacent seedzones rather than all from a local seedzone; seedzone sizes and transfer rules may be broadened; and redundancy of germplasm over a range of sites increased. A small proportion of seed from a broad mix of zones may even be included, especially if these can be tracked in the plantation.

Revisiting and measuring established provenance, transplant studies, and plantations of known germplasm origins over time may provide insight into performance as climate shifts over the sites.

Traditional best genetic management practices will become even more important to implement under changing climates. Paying attention to balance of genetic diversity within seedlots and outplanting collections (i.e., maintaining high effective population sizes) is prudent: maximizing the number of parents, optimizing equal representation by parents (e.g., striving for equal numbers of seeds/seedlings per family), and thinning plantations such that existing genetic diversity is not greatly reduced. Genotypes known or selected for broad adaptations should be favored. By contrast, although economic incentives may override, using a single or few genotypes (e.g., a select clone or small clonal mix) is a riskier choice in a climate change context.

Establish "Neo-Native" Locations. Information from historic species ranges and responses to climate change offers a different kind of insight into the future than modeling studies might. For instance, areas that supported species in the past under similar conditions to those projected for the future might be considered sites for new plantations or "neo-native" stands of the species (Millar, 1998). When these are disjunct from the current native range, or expand into different environments, they have the added potential benefit of escaping native ranges of associated harmful insect or disease organisms. An example is planting Monterey pine (*Pinus radiata*) in areas along the coast of California where it grew under historic climates similar to those projected for the future (Millar, 1998, 1999). Planting giant sequoia (*Sequoiadendron giganteum*) in mixed-conifer forests beyond its current native range in the western Sierra Nevada, a practice that has been done for other reasons, is another example. Note that this perspective on historic distributions is very different from the commonly applied practice of using "historic range of variation" as a reference target for restoration. The latter is a flawed strategy in that it does not take into account the climate conditions when selecting an historic reference period (Millar, 2004; Millar and Brubaker, 2006).

Experiment with Refugia. Plant ecologists and paleoecologists recognize that some sites appear more buffered against climate and short-term disturbances while others are sensitive. If such environments can be identified locally, they could be considered sites for longterm retention of plants, or even for new plantations. Other aspects notwithstanding (such as fire and insect/disease risk), areas of high site quality in the ecological middle of a species' distribution range are likely places to consider as refugial. Unusual soil types such as serpentines and other ultramafic soils, highly podsolized and acidic soils such as underlie the pygmy forests of the California coast, volcanic "scablands" as in the California Cascades and Modoc Plateau, basic soil profiles that occur in small patches along the western Great Basin, and riparian zones of all types typically supported stable plant communities over long historic periods. Where plants have the physiological capacity to cope with nutrient and soil-structural demands, these areas might be considered for experimental refugial plantings.

Promote Porous Landscapes. A capacity to move in response to changing climates is key to adaptation and long-term survival of plants in natural ecosystems. Plants migrate, or “shift ranges” by dying in unfavorable sites and colonizing favorable edges including internal margins. Capacity to do this is aided by porous landscapes, that is, landscapes that contain continuous habitat with few physical or biotic restrictions, and through which plants can move readily (recruit and establish). Factors that hinder porosity include highly fragmented landscapes; forestland converted to development (structures, roads, or urban areas); intensively managed landscapes and small land-allocation sizes; presence of aggressive invasive species; high fire risk; altered, narrow, or absent riparian zones; inflexible management goals for landscape units; and lack of appropriate fire regime or stand structural conditions for species to seed and establish. Promoting large forested landscape units with flexible management goals that can be modified as conditions change will encourage species to respond naturally to changing climates and enable managers to work with rather than against the flow of change.

A porous mindscape is also advantageous under uncertain and changing times. Recognizing, for instance, that species ranges are fluid naturally over time, and that many of our extant forests established during the Little Ice Age and are still in rebound from those cold centuries, is a step toward understanding future changes. Demanding that a species remain only within their 20th century range, considering a species invasive if it expands beyond historic range (e.g., Monterey pine, Millar, 1998), assuming site capacities for timber production are static over time, evaluating mortality only as a sign of poor management rather than a response to changing climates, or assuming that the human footprint of land use does not greatly affect plant response all will hinder species’ adaptation rather than help.

Conduct ***Triage***

Species, plant communities, regional vegetation, and plantations will respond to changing climates individualistically. Some species and situations will be sensitive and vulnerable. Depending on their value or risk level, these may be targeted either for aggressive intervention, or, conversely, intentionally relinquished to their fates. Sensitive conditions often include steep ecotonal conditions; upper and lower elevation edges of species ranges and other range margins (alpine species are especially at risk of moving off the tops of peaks with warming temperatures); mountain regions, which in general are experiencing earlier and more extreme climate changes than lowlands; overly frequent fires (that exceed species’ generation times) or not enough fire (fire-dependency for stand health and seed establishment); high threat from invasive species and/or insects and pathogens; in arid portions of the west, riparian and other water-dependent vegetation types; and plantations or forest conditions of low genetic, structural, and compositional diversity (monocultures, single age classes, large unit areas).

By contrast, there will be other species and situations that are buffered, at least initially, from effects of climate changes or resilient to climate-influenced disturbances. These may need little attention or minimal modifications of management plans, at least in the near future. Decision-support tools that help managers weigh risk levels, project expected benefits or impacts from intervention, evaluate priorities, and develop simple management alternatives must be developed.

Conclusions

Change is a natural and ongoing aspect of earth's complex climate system. Since the 1970s, the interaction of climate-driving mechanisms has shifted to become dominated by anthropogenic influence, predominantly GHG emissions. As a result, climate of the 21st century and beyond will react in different ways than in the past, and will increasingly extend beyond relevant historic ranges of variation. Direct effects of CO_2 on plants will have both detrimental and beneficial effects, depending on species and context. Current projections for California's climate future suggest warming temperatures by 1-5°C and somewhat drier (or wetter). If these result, more precipitation will fall as rain rather than snow, mountain snowpacks will be greatly reduced, winters will be shorter, streamflows will decline, and the already extensive summer drought will be longer and more severe.

Perhaps most importantly, regardless of historic precedence, rapid changes in climate, increasing temperatures, and increases in extreme events are much more difficult for modern society (including the forestry sector) to cope with than in times when human population was more flexible. Our dependence on stable and predictable conditions has led to situations where even historically natural levels of climate variability will have increasingly serious health and economic consequences worldwide. Global political opinion, with some exceptions, is in agreement that the next 50-100 years must be a period when GHG emissions and atmospheric concentrations are brought into control. Managing carbon and coping with climate changes will be the tacit context for vegetation management in the coming century.

In the face of these changes, vegetation managers can help to mitigate ongoing climate changes and GHG emissions, plan strategies to adapt to change, and take actions to conserve energy use and relieve stress on ecosystems. Management practices are grouped under five "Rs", Reduce and sequester greenhouse gases, Resist change, Resile after disturbance, Respond to change, and conduct TRiage.

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Figures

Figure 1. Nested temperature cycles at decadal (top; Pacific Decadal Oscillation), century (middle; Bond cycles), and millennial (bottom; Milankovitch cycles) scales. Cycles are driven by different mechanisms; decadal by ocean circulation and sea temperature, century by solar variability, and millennial by changes in earth's orbit around the sun. These and other cycles interact continually and, in combination, result in ongoing gradual and abrupt changes in earth's natural climate system. From Millar, 2003.

Figure 2. Logs from a Medieval-aged forest dating from 815–1350 CE preserved on the otherwise barren summit of Whitewing Mtn., eastern Sierra Nevada, 3050 m. Straight-stemmed, fast-growing trees grew during the warm Medieval climate in locations that are now above local treeline. The Whitewing forest included *Pinus albicaulis, P. contorta, P. monticola, P. jeffreyi, P. lambertiana* (pictured), and *Tsuga mertensiana,* an assemblage that does not occur now. At present, these species reach upper range limits that are 200-800 m lower than the Whitewing site; *P. lambertiana* currently does not grow east of the Sierra crest. From Millar et al., 2006.

Figure 3. Global mean surface air temperature changes (°C) over the past 140 years (top), from the instrumental record, and 1000 years (bottom), from a multi-proxy record before 1880. Confidence bars and bands are given. From IPCC, 2001.

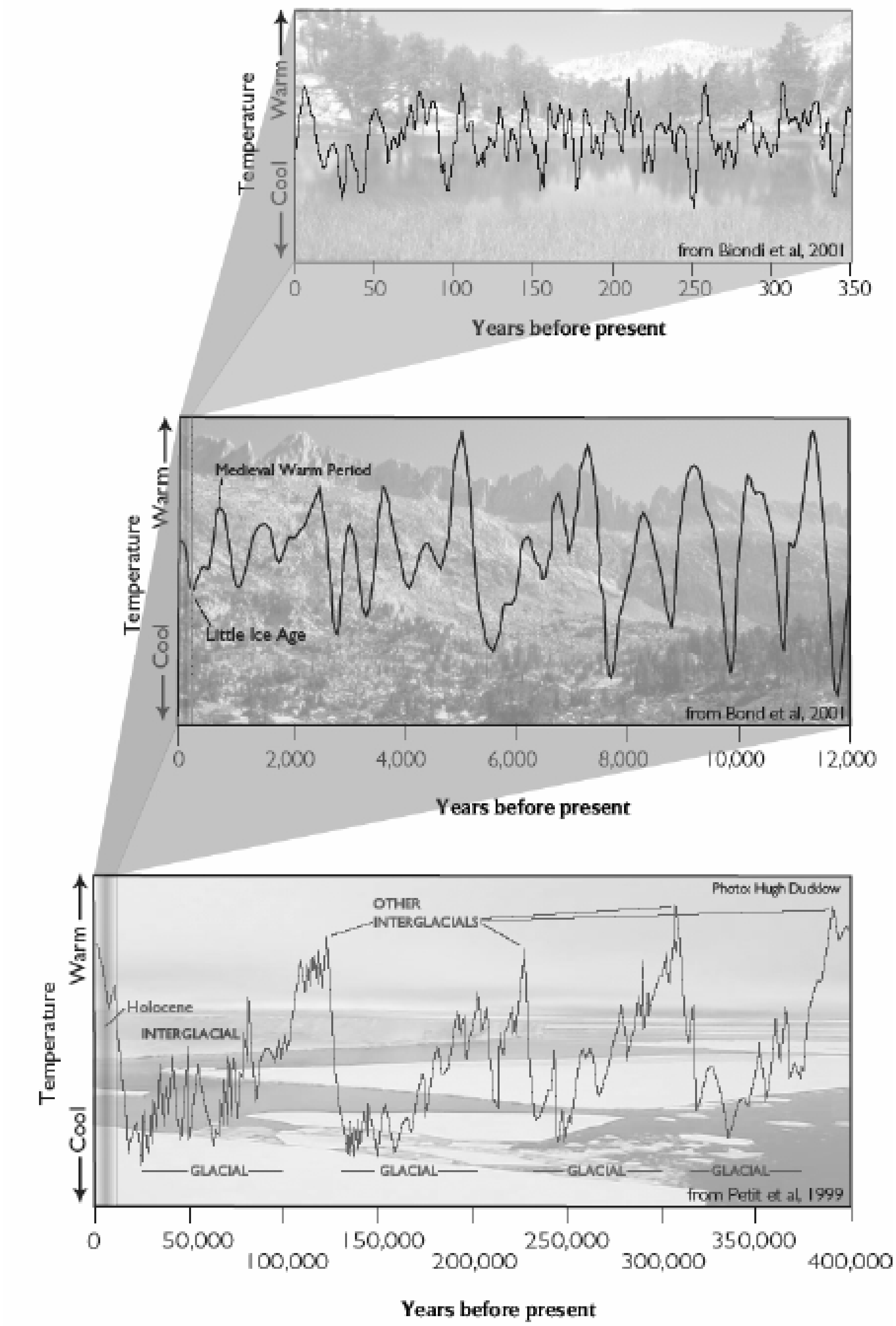
Figure 4. Global mean surface air temperatures (°C) projected for the 21st century and plotted with the observed temperature trend prior to 2001. Multiple lines after 2100 indicate different results from climate models; bars show ranges for each model. From IPCC, 2001.

Figure 5. Annual area burned (ha) by wildfire in the western United States. From Westerling, 2005.

Figure 6. Climate, hydrologic, and mortality projections for California for the periods 2020-2049 and 2070-2099 relative to 1961-1990. From Hayhoe et al., 2004.

Figure 7. Projected changes in forest types for California at 2070-2099. Forest types are: ASF: alpine/subalpine, ECF: evergreen conifer, MEF: mixed evergreen forest, MEW: mixed evergreen woodland, GRS: grassland, SHB: shrubland, DES: desert. Different colored bars are results from the four climate models indicated. From Hayhoe et al., 2004.

Figure 8. Mt Lassen power plant, an electricity-producing facility fueled by biomass from small diameter forest trees. Photo credit: Tad Mason.



Temperature
Warm
Cool
from Biondi et al, 2001
0
50
100
150
200
250
300
350
Years before present
Medieval Warm Period
Little Ice Age
from Bond et al, 2001
0
2,000
4,000
6,000
8,000
10,000
12,000
Years before present
Photo: Hugh Ducklow
OTHER
INTERGLACIALS
Holocene
INTERGLACIAL
GLACIAL
GLACIAL
GLACIAL
GLACIAL
from Petit et al, 1999
0
50,000
100,000
150,000
200,000
250,000
300,000
350,000
400,000
Years before present

Figure 1

Figure 2

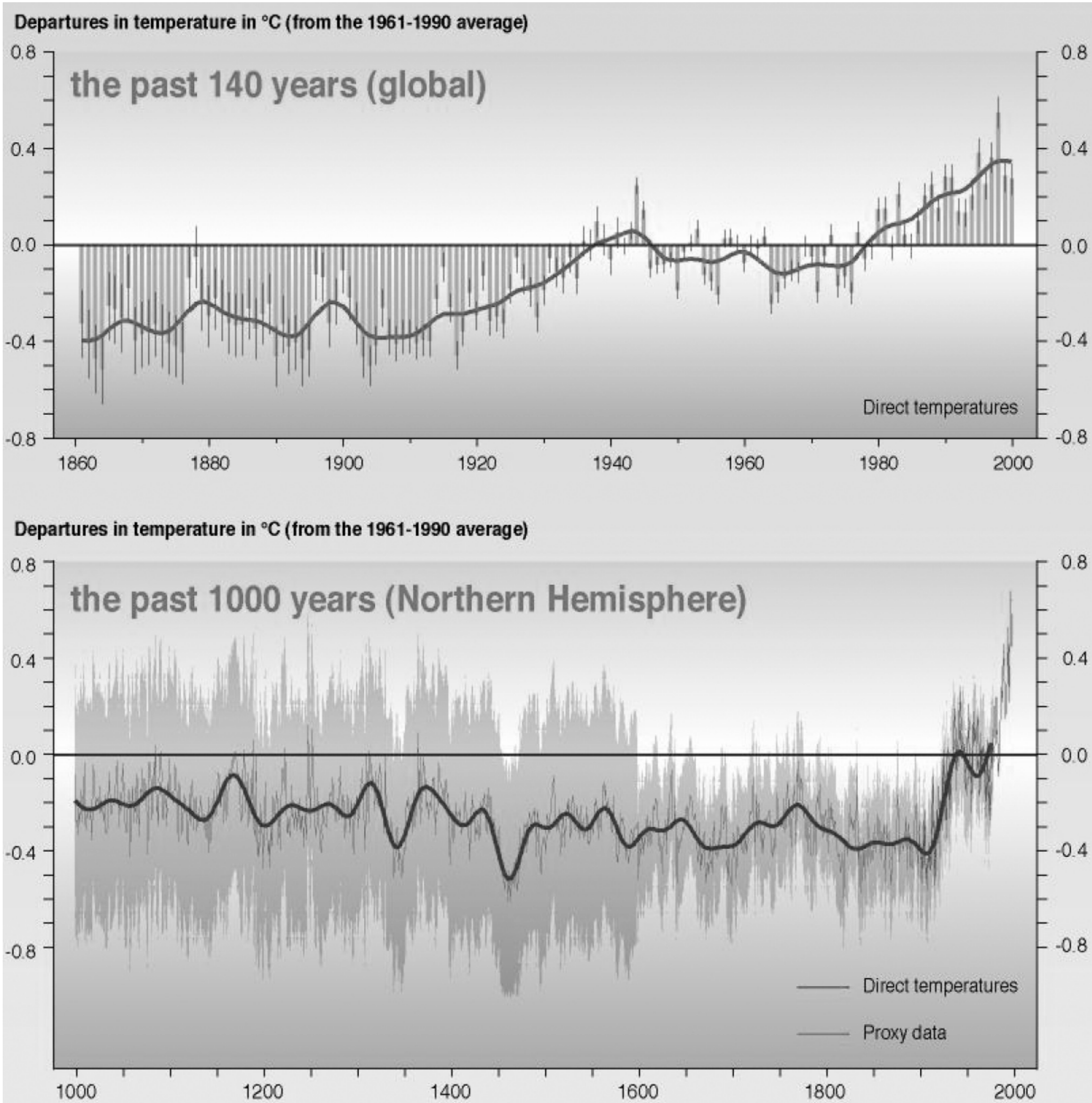

Departures in temperature in °C (from the 1961-1990 average)
the past 140 years (global)
Direct temperatures
0.8
0.4
0.0
-0.4
-0.8
1860
1880
1900
1920
1940
1960
1980
2000
Departures in temperature in °C (from the 1961-1990 average)
the past 1000 years (Northern Hemisphere)
Direct temperatures
Proxy data
1000
1200
1400
1600
1800
2000

Figure 3

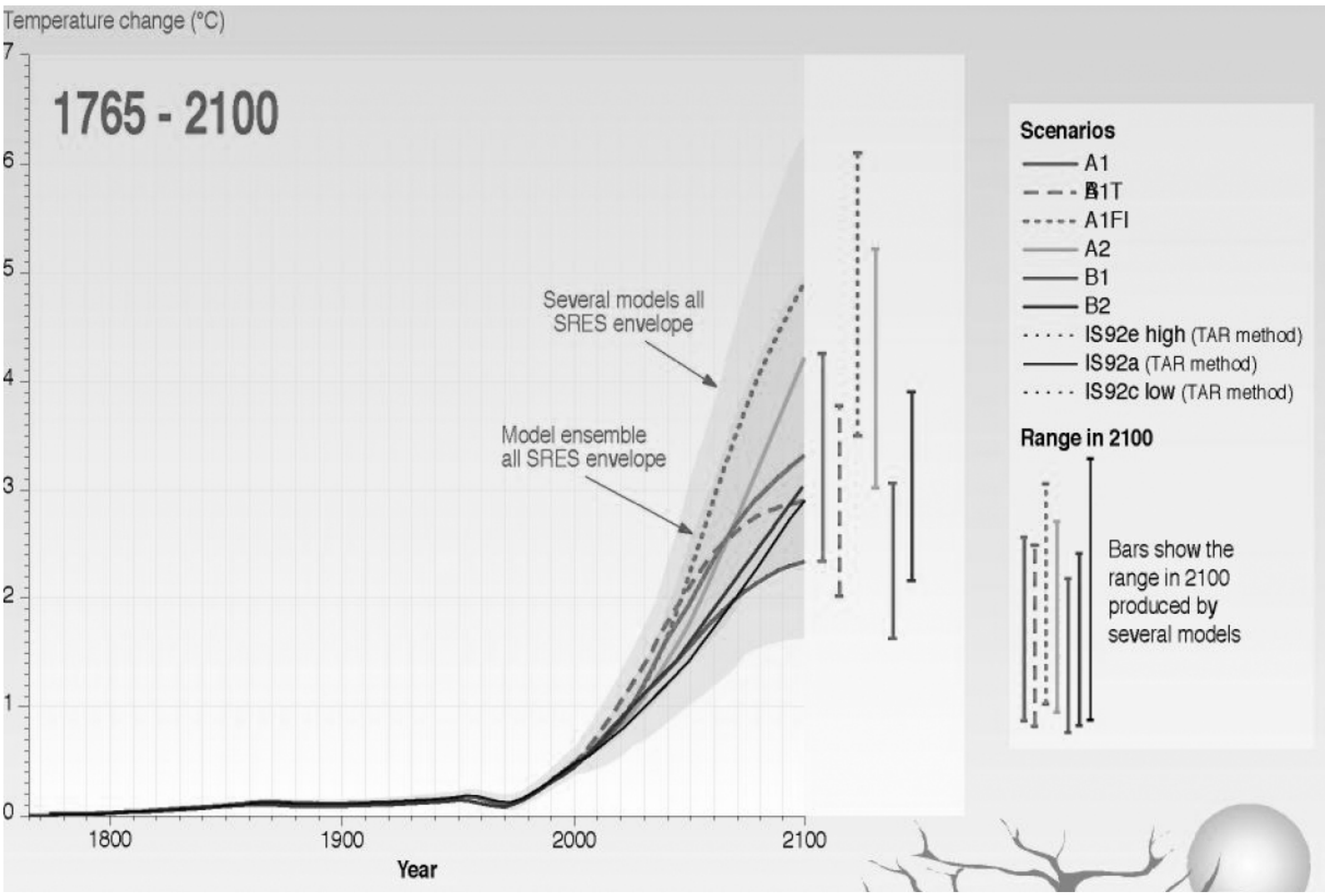

Temperature change (°C)
1765 - 2100
7
6
5
4
3
2
1
0
1800
1900
2000
2100
Year
Several models all SRES envelope
Model ensemble all SRES envelope
Scenarios
A1
A1T
A1FI
A2
B1
B2
IS92e high (TAR method)
IS92a (TAR method)
IS92c low (TAR method)
Range in 2100
Bars show the range in 2100 produced by several models

Figure 4

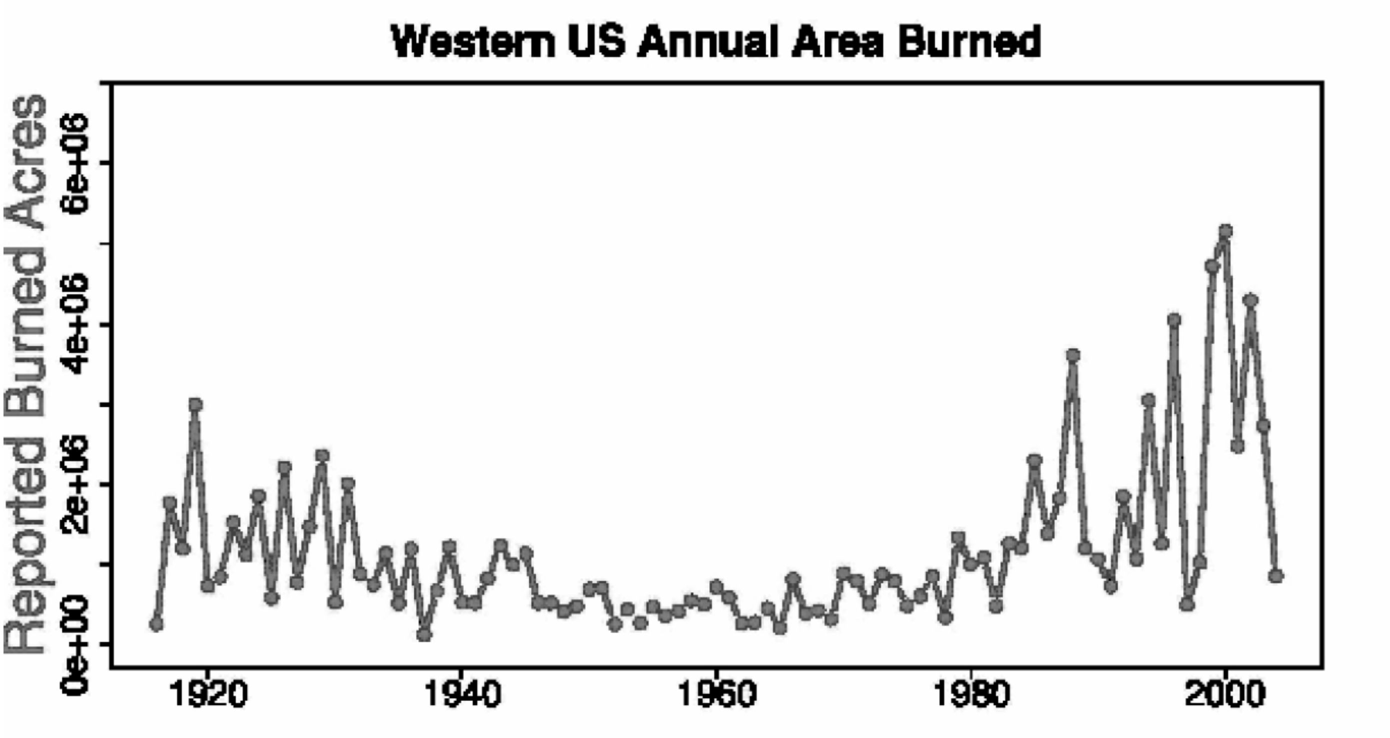

Western US Annual Area Burned
Reported Burned Acres
0e+00
2e+06
4e+06
6e+06
1920
1940
1960
1980
2000

Figure 5

			2020–2049				2070–2099			
			PCM		HadCM3		PCM		HadCM3	
	Units	1961–1990	B1	A1fi	B1	A1fi	B1	A1fi	B1	A1fi
Change in statewide avg temperatures										
Annual	°C	15.0	1.35	1.5	1.6	2.0	2.3	3.8	3.3	5.8
Summer (JJA)	°C	22.8	1.2	1.4	2.2	3.1	2.15	4.1	4.6	8.3
Winter (DJF)	°C	7.6	1.3	1.2	1.4	1.45	2.15	3.0	2.3	4.0
Change in statewide avg precipitation										
Annual	mm	544	−37	−51	+6	−70	+38	−91	−117	−157
Summer (JJA)	mm	20	−3	+2	−1	−7	+4	−46	−5	−1
Winter (DJF)	mm	269	−45	−55	+4	−44	+13	−13	−79	−92
Sea level rise	cm	—	8.7	9.5	11.6	12.7	19.2	28.8	26.8	40.9
Heatwave days										
Los Angeles	Days	12	28	35	24	36	44	76	47	95
Sacramento	Days	58	91	101	93	104	109	134	115	138
Fresno	Days	92	113	120	111	116	126	147	126	149
El Centro	Days	162	185	185	176	180	191	213	197	218
Length of heatwave season*	Days	115	135	142	132	141	149	178	162	204
Excess mortality for Los Angeles†										
Without acclimatization	avg no. of deaths/yr	—	—	—	—	—	394	948	667	1,429
With acclimatization	avg no. of deaths/yr	165	—	—	—	—	319	790	551	1,182
Change in April 1 snowpack SWE										
1,000–2,000 m elevation	%	3.6 km^3	−60	−56	−58	−66	−65	−95	−87	−97
2,000–3,000 m elevation	%	6.5 km^3	−34	−34	−24	−36	−22	−73	−75	−93
3,000–4,000 m elevation	%	2.3 km^3	−11	−15	4	−16	15	−33	−48	−68
All elevations	%	12.4 km^3	−38	−37	−26	−40	−29	−73	−72	−89
Change in annual reservoir inflow‡										
Total	%	21.7 km^3	−18	−22	5	−10	12	−29	−24	−30
Northern Sierra	%	15.2 km^3	−19	−22	3	−9	9	−29	−20	−24
Southern Sierra	%	6.5 km^3	−16	−23	10	−14	17	−30	−33	−43
Change in April–June reservoir inflow‡										
Total	%	9.1 km^3	−20	−24	−11	−19	−1	−46	−41	−54
Northern Sierra	%	5.5 km^3	−21	−24	−16	−19	−6	−45	−34	−47
Southern Sierra	%	3.6 km^3	−18	−24	−2	−19	5	−47	−52	−65
Change water year flow centroid‡										
Total	Days	03/26	0	2	−15	−7	−7	−14	−23	−32
Northern Sierra	Days	03/13	0	3	−16	−5	−3	−11	−18	−24
Southern Sierra	Days	05/01	−10	−7	−19	−12	−22	−34	−34	−43

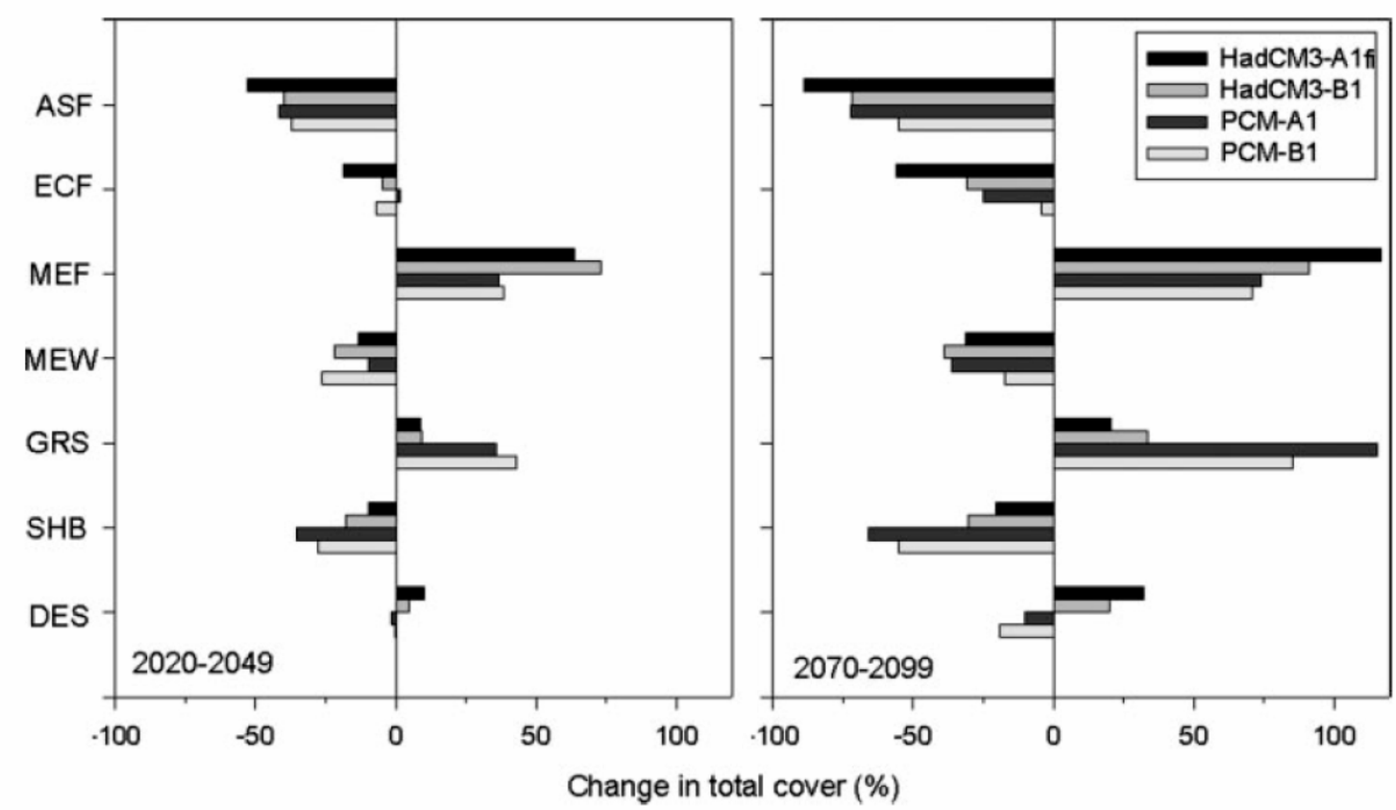
avg, average; JJA, June, July, August; DJF, December, January, February; SWE, snow water equivalent.

*The number of days between the beginning of the year's first and end of the year's last heatwave.

†Reference period is 1990–1999, and projections are for the period 2090–2099.

‡Results are for inflows to seven major dams and reservoirs in the Sacramento/San Joaquin water system, including three in the Northern Sierra (Shasta, Oroville, and Folsom) and four in the Southern Sierra (New Melones, New Don Pedro, Lake McClure, and Pine Flat).

Figure 6



HadCM3-A1fi
HadCM3-B1
PCM-A1
PCM-B1
ASF
ECF
MEF
MEW
GRS
SHB
DES
2020-2049
2070-2099
-100
-50
0
50
100
Change in total cover (%)

Figure 7

Figure 8