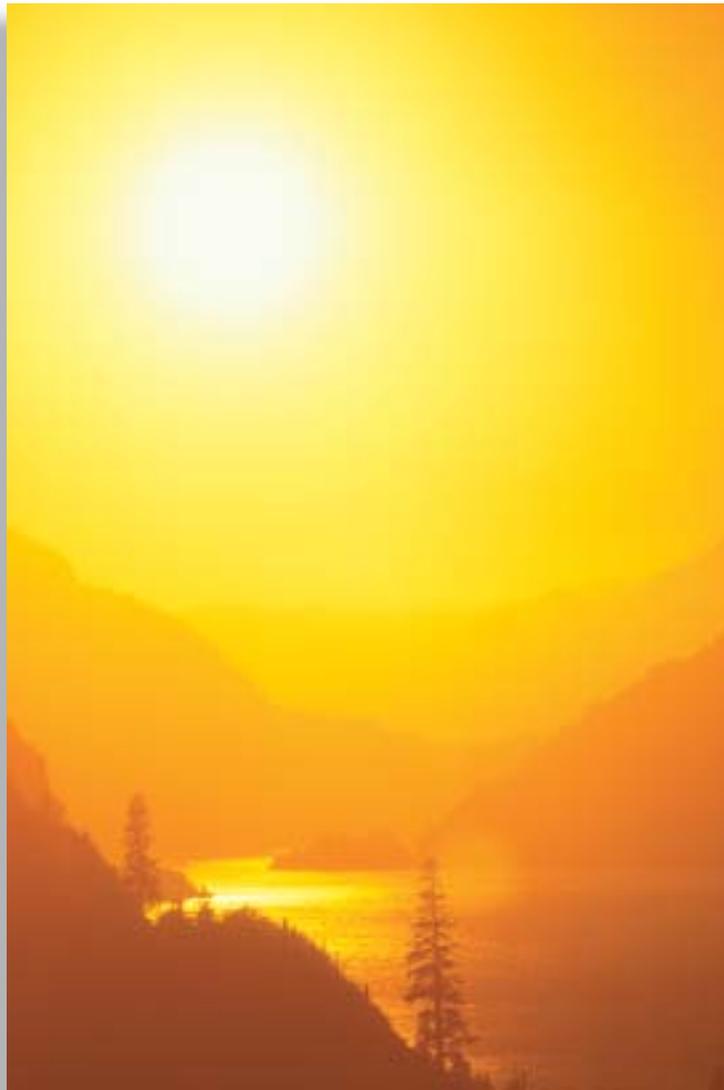# Forests, Carbon and Climate Change

A Synthesis of Science Findings

Forests, Carbon and Climate Change

A Synthesis of Science Findings

A project of

The Oregon Forest Resources Institute

Oregon State University College of Forestry

Oregon Department of Forestry

CHAPTER THREE
HIGHLIGHTS:
CLIMATE CHANGE AT MULTIPLE SCALES

Introduction

■ Climate change is a key driver of historic vegetation change.
■ Understanding climate change is important to the stewardship of forests.

The Natural Climate System — Overview

■ New tools, computing capacity and research have revealed much about past climate.
■ Climate naturally cycles, with major warm and cold periods, and shorter nested cycles.
■ Climate often changes abruptly, and often vegetation response is dramatic.

The Natural Climate System — A Primer on Past Climates

■ The earth has experienced more than 40 warm and cold cycles during the Quaternary Period, i.e., the past 2.5 million years ago.
■ Climate changes in multiple cycles, from multi-millennial to those that last a few years or decades, and worldwide evidence shows life on earth has responded on each scale.

Implications of Natural Climate Change for Vegetation Ecology

■ Ecological conditions constantly change in response to climate, and species shift even in the absence of human influence.
■ Currently, species ranges and demographics are expected to be highly unstable.

The Human-Dominated Climate System

■ Recent global average temperature is higher than the past 1,000 years.
■ Trends since 1975 can only be explained by non-natural forces.
■ Future scenarios depict increases of approximately 2.7 to 10.4 °F by 2100 and an increase in carbon dioxide concentrations of 575-1000 parts per million.
■ Even with CO_2 decreases, atmosphere would not stabilize for 100 to 300 years.

Potential Impacts of Climate Change on Oregon Ecosystems

■ Most scenarios show temperature increases from about 7 to 8 °F from the present time to the end of the 21st century.
■ The growing season could lengthen at least four to six weeks.
■ In models, precipitation decreases 10-40% in summer; in winter has a range from 10% decrease to 24% increase.
■ Biomes could change dramatically; shrubland/grassland could disappear.
■ Vegetation distribution could have significant decreases and expansions.
■ Wet maritime forests would lose carbon, while dry ecosystems gain carbon.
■ Suppression of fire vs. uncontrolled fires greatly alters all the scenarios.

Summary

■ Even with the latest techniques, projections about future climates are difficult to forecast.

CHAPTER THREE
CLIMATE CHANGE AT MULTIPLE SCALES

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Introduction

Concepts about the natural world influence approaches to forest management. In the popular press, *climate change* inevitably refers to global warming, greenhouse gas impacts, novel anthropogenic (human-induced) threats, and international politics. There is, however, a larger context that informs our understanding of changes that are occurring – that is, Earth's natural climate system and its variability.

Climate change is a central focus 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 over thousands of years have triggered speciations (lineage-splitting events that produce two or more species), and the evolution of major adaptations among and within species. On scales of decades and centuries, smaller climate changes have driven mixing and re-mixing of plant communities and catalyzed shifts in population size. Much as we have come to terms in vegetation ecology with the concepts of dynamism, such as the roles of fire, flood, and insects, we tend to view these successional changes against a static background. Significant historic climate changes are often considered events of the past with little relevance to the present or future. To the contrary, climate changes, often abrupt and extreme, characterize the ongoing stream of natural climate.

Without understanding these natural climate processes and the ways in which forest species are adapted to climate changes, decisions may be made that are counter-productive to the forests we wish to steward. Further, greater awareness of the natural climate system can put in perspective the specific effects of human-induced climate changes. In the past decade, scientists have recognized that a new, human-dominated climate system has emerged that diverges in significant ways from the natural system (IPCC 2001). This brings additional challenges to forest management beyond coping with natural changes in climate. Because of the long residence time of carbon dioxide in the atmosphere, the human influences on the current trajectory appear to be irreversible for decades to centuries, even with mitigation. Thus, given the dynamics of the natural climate system and the superimposed changes humans are causing, the 21st century is an important transitional time for undertaking both mitigation and adaptation actions.

Given this, what can forest and resource managers of private and public forest lands do to address these challenges responsibly? While we begin here to outline new management strategies for a climate context, detailed case studies and demonstrations haven't yet been fully developed. These 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 outline natural climate patterns and mechanisms as important context for understanding current and future changes. Further, we provide an update on conditions of the human-dominated climate system, especially in the Pacific Northwest, and finally, briefly introduce five general principles for vegetation management in the face of the climate change.

The Natural Climate System — Overview

Changes in weather are familiar features of Earth's surface, readily recognizable as daily 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. Without direct methods for understanding past climate variability, there was no reason to believe that the past climate was relevant to the present. All this changed with the advent of new methods.

Climate Oscillates

In the past two decades, new tools with high precision and resolution, new theory based 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 randomly or follow pervasive linear trends (*Figure 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 potential for drought.

Figure 1

Global temperature cycles. a) Decadal cycles driven by ocean circulation and sea temperatures, b) Century cycles driven by solar variability, c) Millennial cycles driven 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. Source: Millar, 2003.
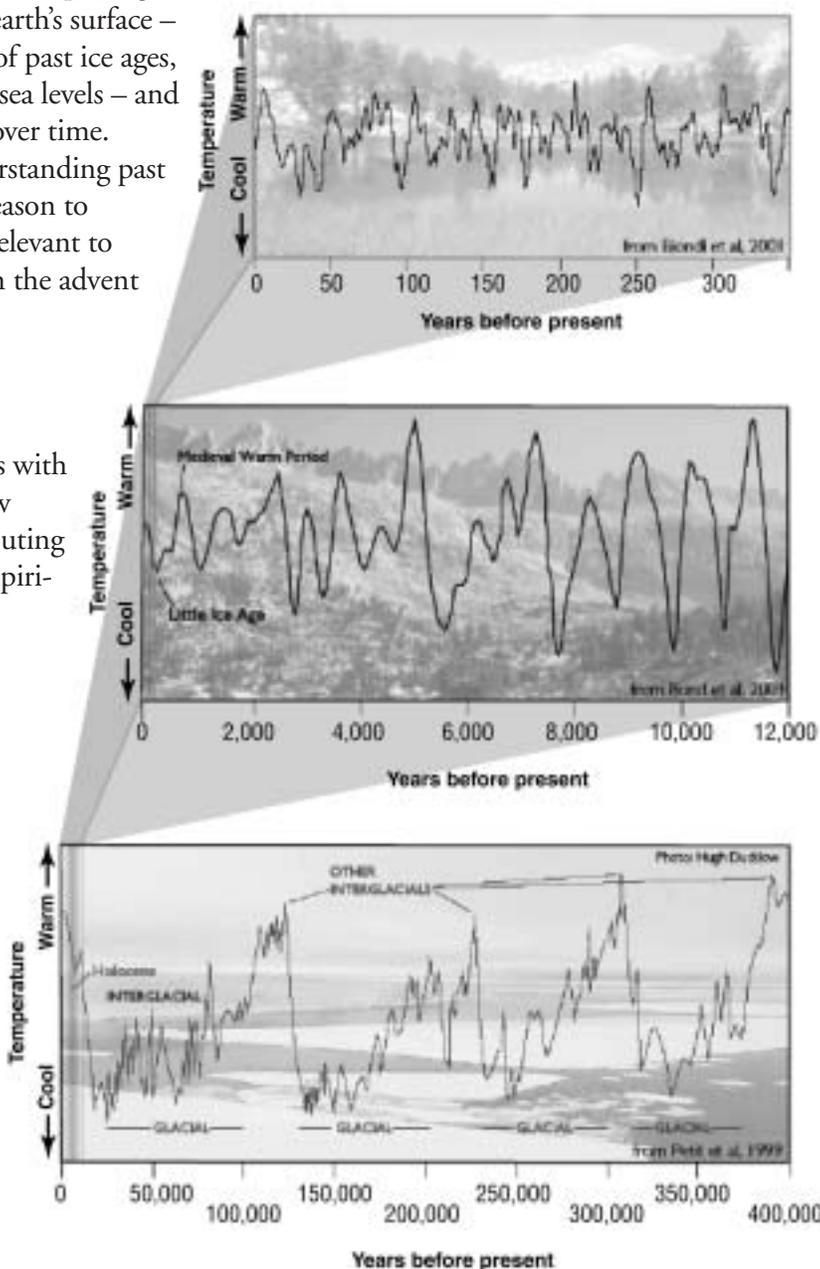
Climate Cycles at Multiple Scales

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 (*Figure 1*), and which are caused by independent physical mechanisms. Major interglacial (warm) and glacial (cold) periods cycle on multi-millennial scales. These are caused by oscillations in earth's orbit around the sun, which in turn, control significant temperature changes. At the century scale, recurring variations in the sun's activity drive cycles of about 1200-year periods. The now familiar El-Niño/La Niña cycle (called ENSO, for El-Niño Southern Oscillation) is an example of changes at the interannual scale, and a similar 30 to 40 year oscillating pattern in the Pacific Decadal Oscillation (PDO) affects the west coast of North America. These shorter cycles result from mechanisms internal to earth, that is, the cyclic patterns of ocean circulation and ocean temperature. The separate mechanisms of these various cycles interact and feed back 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, the science of past climate informs us that major and minor transitions in climate state often occur *abruptly* (a few years to decades). Climate states are highly sensitive, catalyzed by threshold and feedback events, triggered by random 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, with switches to glacial climates occurring in only a few decades. 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 surface air temperature, precipitation, 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, resulting in changes in streamflow, groundwater, 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.

In the following sections, we give additional details on basic principles of natural climate variability.

The Natural Climate System – A Primer on Past Climates

The most widely applied new method for understanding past climates — studying core samples — was first derived from long ice cores drilled into polar ice caps (Cuffey *et al.* 1995). Gases and atmospheric particles trapped in ice faithfully record atmospheric conditions at the time of deposition. Due to annual layering and the ability to date layers accurately, analysis of thin sections at regular intervals yields high-resolution historic climate data in a continuous time series. Cores drilled to the bottom of continental ice sheets (e.g., Greenland) have yielded high-resolution information on more than 40 climate variables that extend over 200,000 years (Lorius et al., 1990). The most important are isotopes of oxygen. Ratios of heavy to normal oxygen isotopes (^{18}O) quantify the relative amount of oxygen stored in land ice relative to seawater, and provide strong indicators of surface air temperature at the time the isotopes were trapped in the ice. Analysis of these and other climate-related isotopes are now routinely extracted from other situations where undisturbed deposition occurs, such as lake beds, coral reefs, and sea floor sediments. Depending on the depth of the

deposition and the time interval between sections analyzed, such sediment cores yield detailed climate information at multi-millennial to interannual scales, as we summarize below.

Multi-Millennial Climate Cycles

Taken together, these long records collectively document the repeating, cyclic nature of climate during the Quaternary, or past 2.5 million years (*Figure 2*, Wright 1989; Raymo and Ruddiman 1992). Unlike earlier assumptions of persistent ice ages, oxygen-isotope records show a repeating pattern of over 40 glacial (cold) /interglacial

abrupt transitions, into the cold of another glacial period. The cumulative effect is a sawtooth pattern typical of Quaternary climate records around the world (Figures 1, 2).

Importantly, the pattern of historic temperature change synchronizes with changes in carbon dioxide and methane. Concentrations of carbon dioxide (CO_2) during previous warm interglacial periods were about the same as the peak natural levels of the Holocene (the past 10,000 years), about 300 ppm, while during cold glacial periods, concentrations lowered to 190-200 ppm. The tightly synchronous changes in temperature and greenhouse gases suggest a mechanistic relationship. Although variable CO_2 concentrations are not the primary cause of cold – warm cycles, it is thought that they played a role. There were times when changes in CO_2 concentration preceded changes in temperature and vice versa.

The leading theory is that as glaciers advance, the CO_2 concentration is reduced through increased carbon sequestration in the oceans and ocean sediments, creating a negative feedback inducing further cooling. However, when the planet begins to warm, CO_2 is released from the oceans, creating a positive feedback and increasing the rate of warming. It is estimated that about half of the glacial – interglacial temperature change is due to the greenhouse gas feedbacks (Petit *et al.*, 1999). This may help explain the asymmetry observed in glacial – interglacial cycles, with slow cooling and rapid warming. The potential CO_2 increase through the 21st century may be sufficient (at the upper end of the uncertainty bounds) to induce a temperature increase that is of the magnitude of a full glacial – interglacial cycle (IPCC 2001).

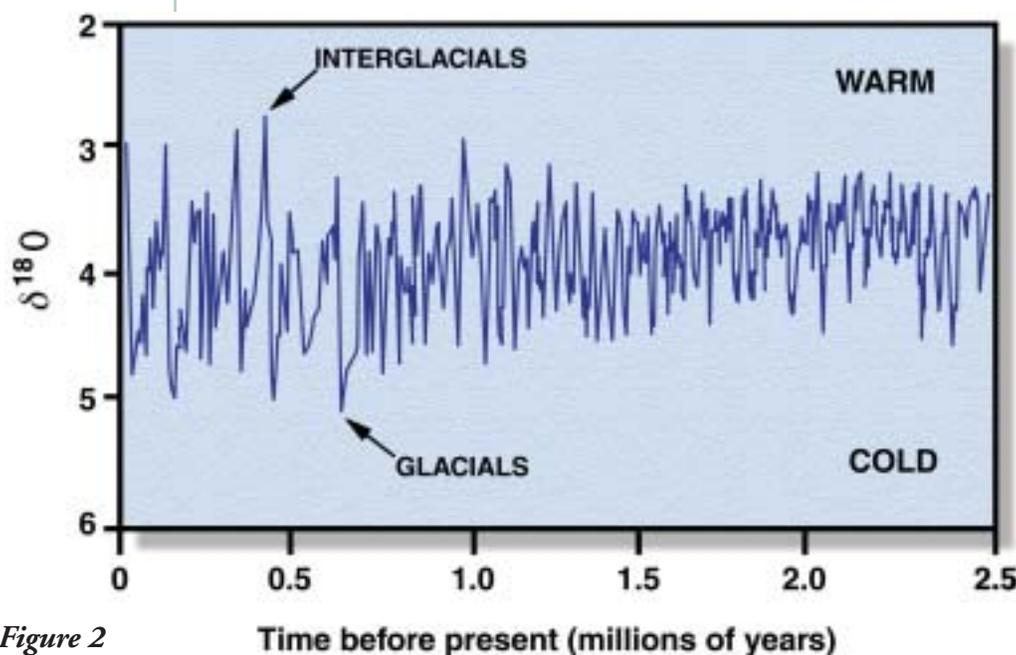A mechanistic cause for the overall glacial/interglacial climatic oscillations was proposed by Serbian

Figure 2

Temperature fluctuations between glacial and interglacial periods of the past 2.5 million years. Derived from oxygen-isotope analysis of ice cores from the Greenland ice sheet. Current interglacial period (Holocene) is at the far left, from 0–10,000 years ago. From Wright, 1989.

(warm) cycles, with global temperature differences between cycles averaging 11 to 15°F (Petit *et al.* 1999). A startling insight revealed by the oxygen-isotope records is the overall similarity of our past 10,000 years to similar warm interglacial periods throughout the Quaternary. Recent climate cycles are not wholly novel after all.

The oxygen-isotope data further reveal a repeating structure of climate variability *within* glacial and interglacial phases (Lorius *et al.,* 1990). Extensive cold glacial periods were interrupted by warm periods. A pattern emerged: interglacials began abruptly, peaked in temperature in early to middle cycle, and ended in a series of steps, each with

mathematician Milatun Milankovitch (Milankovitch 1941) long before detailed past-climate variability had been documented. Milankovitch integrated knowledge about earth's orbit around the sun into a unified theory of climate oscillations. This has been revised subsequently into a modern orbital theory that is widely accepted as the mechanism that controls the ice ages (Imbrie *et al.*, 1992, 1993).

Three major cycles of orbital variability recur over time (*Figure 3*, Hays et al. 1976): (1) change in the shape of earth's orbit around the sun from elliptical to circular (100,000 years), (2) change in the angle of earth's tilt on its axis (41,000 years), and, (3) change in time of year when the earth is closest to the sun (23,000 years). The amount of heat from the sun reaching the earth at any point in time varies with the earth's position in each cycle. Integrating the three cycles mathematically results in a curve over time of predicted temperature on earth that corresponds to the observed changes in oxygen-isotope concentration, and thus the sawtooth pattern of periods of warm and cold. (e.g., Figures 1, 2).

Century- to Millennial-Scale Climate Cycles

Within these cycles that extend over tens to hundreds of thousands of years are shorter, orbitally-driven climate cycles or "events" — extremely cold or warm intervals — that last from one hundred to a thousand years. These climate events are increasingly understood as part of a pervasive oscillation pattern, now called "Bond cycles," documented for at least the last 130,000 years (Bond *et al.*, 1997). Bond cycles average 1300-1500 years, meaning that each warm or cold phase lasts about 700 years, and the peak warm and cold phases last about 350 to 450 years (*Figure 4*). Climate intervals during the Holocene that exemplify Bond cycles include the Little Ice Age, a significant ice advance and global cold period from 1450-1920 (Grove 1988; Overpeck et al. 1997); the Medieval Climate Anomaly, a warm, dry interval from 900-1350 (Hughes and Diaz 1994, Stine 1994, Esper *et al.*, 2002); and the so-called 8200 year (ago) cold event (Alley *et al.*, 1997).

Figure 3

Primary orbital cycles of the earth. The fundamental mechanism for oscillating climates of the past 2.5 million years. Temperatures on earth vary depending on how much heat from the sun (solar insolation) reaches earth's surface. This in turn varies depending on the exact position of earth within each of three orbital cycles. Mathematical integration of the three curves produces a graph of temperature over time that closes matches temperature reconstructions from ^{18}O, e.g., Figure 1. Data source: *Science, Variations in the Earth's Orvit: Pacemaker of the Ice Ages. 1976.*
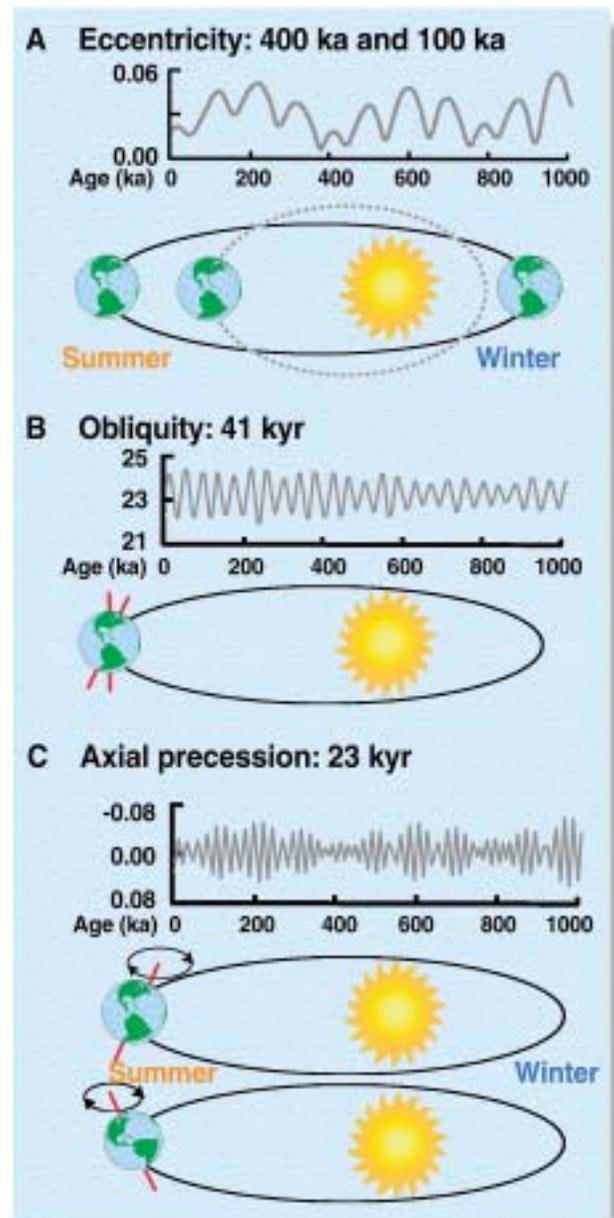
Painstaking analysis at high resolution of several well-known Bond intervals has documented that oscillations often begin and end extremely abruptly. For example, a study of the major collapse of ice at the end of the Younger Dryas cold event (11,500-12,500 years ago) revealed that a 27°F warming occurred in two 10-year periods separated by a 20-year plateau of no detectable temperature change (White *et al.*, 2001).

Of particular interest at this time scale is the warming of the 20th century. During the Little Ice Age (1450-1920) temperatures in western North

America were on average 2°F colder than present; glaciers in many western North American mountain ranges were at their greatest extent since the end of the Pleistocene over 10,000 years ago (Clark and Gillespie 1997). Warming since the late 1800s has been about 1.3 °F globally (IPCC 2001). Increases in the early part of the century are now widely accepted as natural climate forcing, whereas continued warming since mid-20th century can be explained only from recent human-induced greenhouse gases (IPCC 2001, and see section below).

The natural mechanisms driving climate oscillations at the 100 to 1,000 year scale are a topic of current interest. The relationship of extremely cold intervals within glacial periods to sudden surges of polar ice into high-latitude oceans, and resulting abrupt changes in global ocean salinity, first led climatologists to believe these intervals were driven by ice and ocean-circulation dynamics (Broecker *et al.*, 1990, Clark *et al.*, 2001). Recently, however, millennial cycles in the sun's intensity have also been shown to match the timing of the Bond cycles over the last 130,000 years with high precision (Figure 4, Bond *et al.*, 2001). This has led climatologists to speculate that a trigger for 100 to 1,000 year climate changes comes from outside the earth – that is,

changes in the sun – and subsequent changes in ocean circulation and temperature.

Interannual- to Decadal-Scale Climate Change

In recent years, climatologists have defined high-frequency climate cycles from a few years to several decades. The best known of these is the El-Niño/ La Niña pattern (ENSO; Diaz and Markgraf 2000). Every several years, hemispheric trade winds that typically blow warm tropical ocean water westward across the Pacific Ocean stall and instead, warm water accumulates in the eastern Pacific Ocean. This leads to the presence of unusual water temperatures offshore from North and South America. Each year there is some degree of El Niño or its opposite effect, La Niña. Extreme events cycle on a 2 to 8 year basis (*Figure 5*). El Niño events bring different conditions to different parts of the world. For instance, they portend unusually cold and dry weather in the Pacific Northwest but unusually warm and wet fall and winters in central and southern California. The reverse occurs during La Niña events.

Climate oscillations on multi-decadal (20 to 60 year) periods have also been described recently. Like ENSO, these act regionally but have effects on distant locations. The Pacific Decadal Oscillation

Figure 4

100-1,000 year oscillations. Bond cycles have been pervasive at least through the Holocene and last major glacial age. Individual events have long been recognized, such as the Little Ice Age (1450-1900 CE) and the Younger Dryas (11.5-12.5 ka). From Bond *et al.,* 1997, 2001.
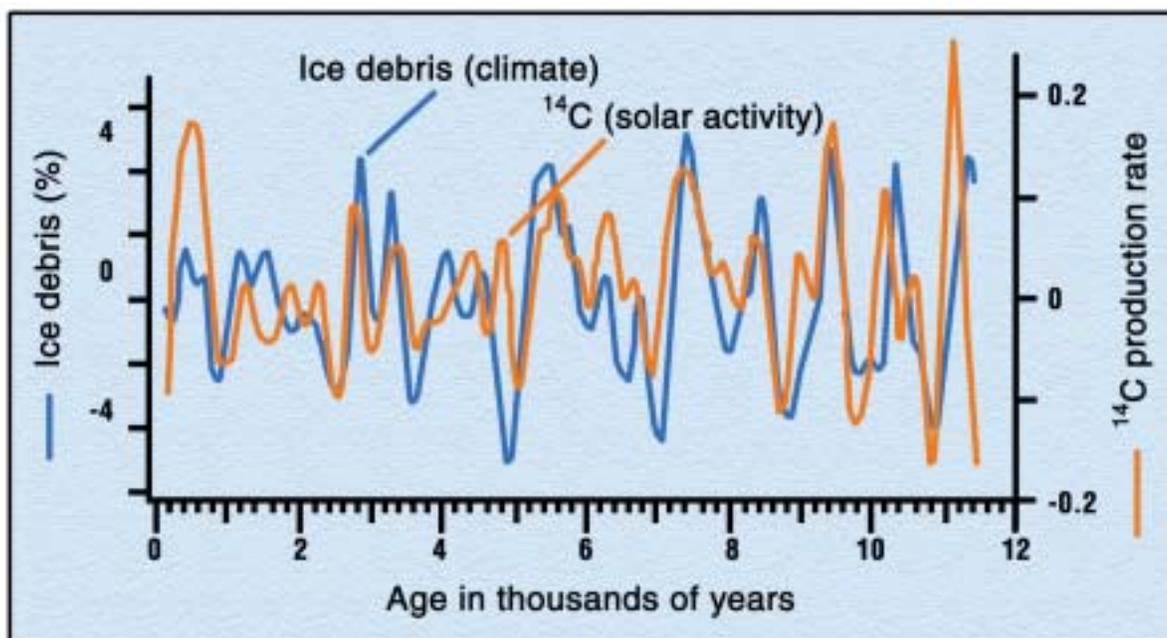
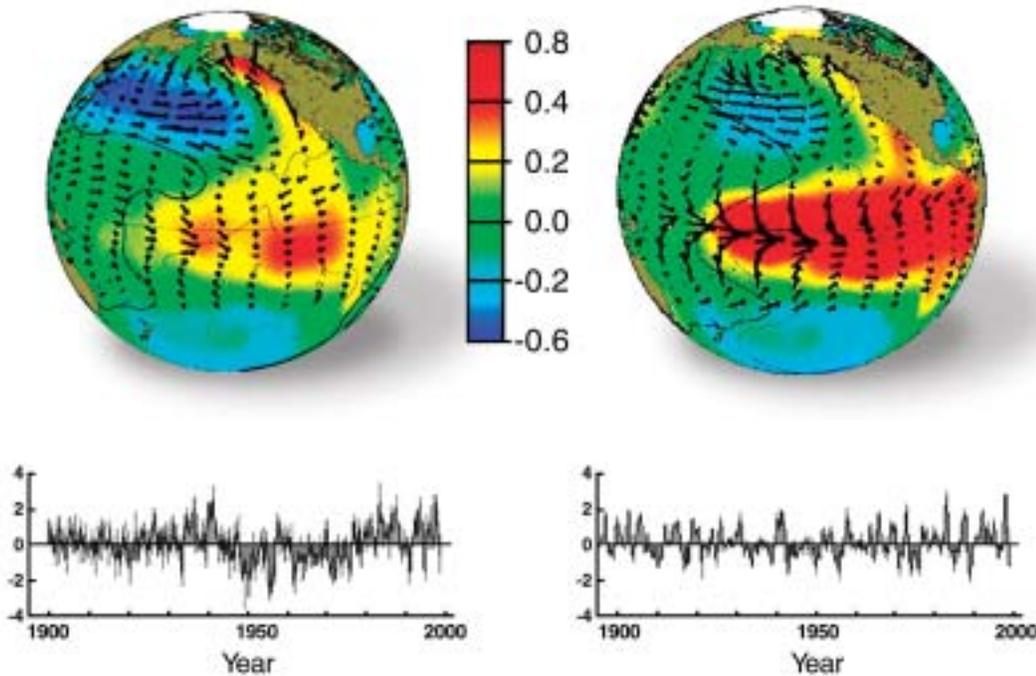## Pacific Decadal Oscillation (PDO)   El Niño/Southern Oscillation (ENSO)

(PDO, *Figure 5*) affects western North America. It appears to be regulated by decadal changes in ocean circulation patterns in the high-latitude Pacific Ocean (as opposed to ENSO's tropical locus), and yields climate effects and regional patterns similar to extended ENSO effects (Mantua *et al.*, 1997, Zhang *et al.*, 1997). Warm (or positive) phases are extensive periods (10 to 25 years) of El Niño-like conditions that alternate with cool (or negative) phases of La Niña-like conditions. Other such multi-decade, ocean-mediated patterns affect other parts of the world (Cronin 1999).

**Climate as a Force of Ecological Change**

Abundant evidence worldwide indicates that life on earth has responded to climate change at each of these scales. Changes in biota over time can be measured in many ways, such as from sediment cores taken from wet areas including meadows, bogs, lakes, and ocean bottoms. In dry environments, packrat middens preserve macrofossils, while in temperate forests, tree-ring records archive annual tree growth.

At *multimillennial* scales, ecological records of the past collectively document that, at any one place, compositions of species changed significantly in

correspondence with major climate phases. Often, changes showed complete species turnover. In relatively flat terrain, such as in northeastern United States, eastern Canada, parts of Scandinavia, and northern Asia, species shifted north and south hundreds of miles, as modeled, for example, for spruce (Picea) in eastern North America (*Figure 6*, Jackson *et al.*, 1987). By contrast, in mountainous regions, plant species

Figure 6

Shift in ranges of spruce (*Picea*) forests in eastern North America. Changing times (*ka* is thousands of years ago) from the Last Glacial Maximum to present . From Webb *et al.*, 1987.

Spruce

18 ka   15 ka   12 ka

9 ka   6 ka   3 ka   0 ka
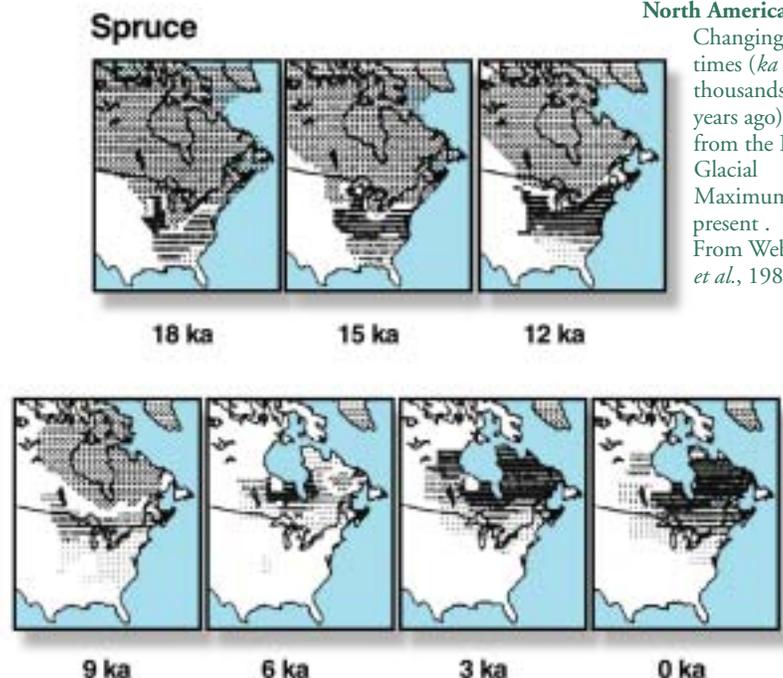
responded primarily by moving in elevation, as indicated by conifers of the Great Basin and southwestern desert region, which shifted as much as 4500 ft (*Figure 7*, Thompson 1988, 1990,

correspond to Bond-scale cycles (Tausch et al. 2004). Whereas recurring patterns emerge at coarse scales, species responses are individualistic, lags are common, and nonlinear patterns frequent, so that population increases or decreases may not appear to be "in synch" with climate change, especially when climate changes are extreme and abrupt (Jackson and Overpeck 2000)
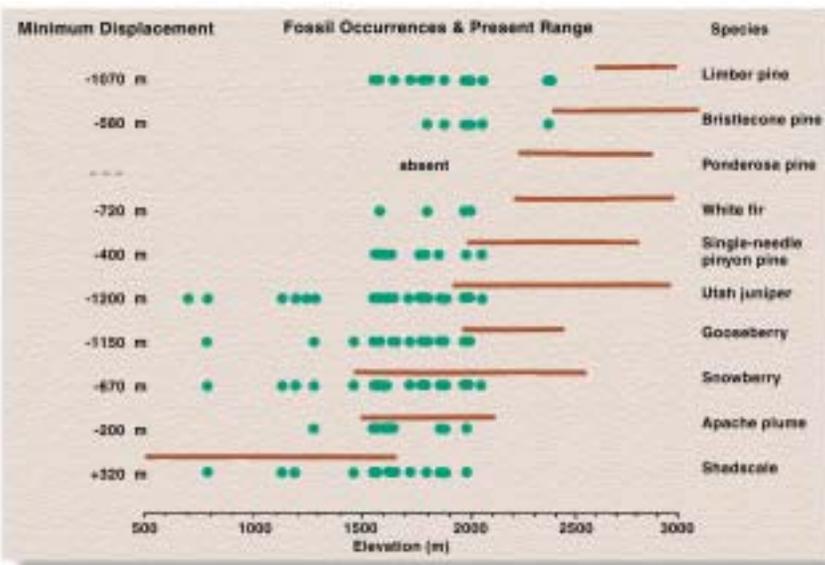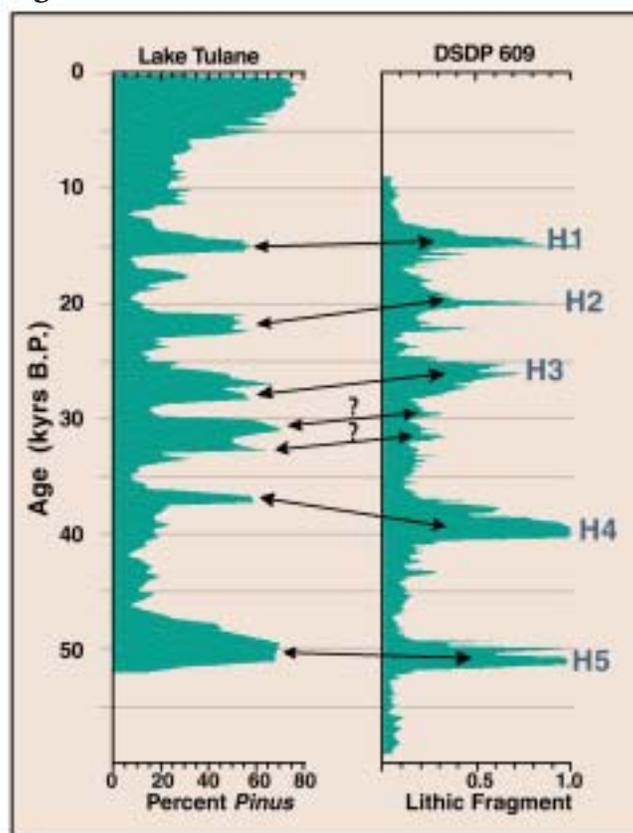
Vegetation responds also to *interannual and decadal* variability. At the ENSO scale, changes occur primarily in plant productivity and abundance within populations. The oscillations contribute to regional fire regimes, where fuel loads build during wet years and burn during dry years (Swetnam and Baisan 2003). These lead to mid-scale vegetation changes as ENSO itself cycles, and thus fire regimes change over time (Swetnam and Betancourt 1998, Kitzberger *et al.*, 2001). Decadal climate and vegetation oscillations have been well-docu-

Figure 7

Glacial/ interglacial shifts in elevation for plant species of the Sheep Range, southern Nevada. Current (solid line) and past (dots) elevation limits, and individualistic responses of species. From Thompson, 1990.

Grayson 1993). Before temperature proxies such as oxygen isotopes provided independent measures of historic climate, millennial-scale abrupt climate events were inferred from changes in flora and fauna. For instance, the Younger Dryas cold interval was known from changes in abundance of the arctic tundra plant *Dryas octopetala* (Jensen 1935).

Significant and rapid response of vegetation to *century* scale climate change is also well-documented, although elevation shifts are lower and migration distances smaller than for longer time scales. Many examples now show fluctuating changes of vegetation corresponding to Bond cycles, which average 1300-1500 years. An illustrative example is the abrupt change in pine versus oak vegetation in southern Florida that corresponds to Heinrich events (extremely cold intervals 100 to 1,000 years ago) (*Figure 8*, Grimm *et al.*, 1993). In California, abrupt changes in the dominance of oak versus juniper corresponded to rapid climate oscillations of the last 160,000 years (Heusser 2000). In the Great Basin of North America, major changes in population size and extent of pinyon pine (*P. monophylla*)

Figure 8

Abundance of pine from Lake Tulane, Florida (indicated by pollen %, left panel) correlates with millennial scale cold, or Heinrich, events of the last glacial period (indicated by % lithics, or ice-rafted rock debris, right panel). Data from Grimm *et al.*, 1993.

mented in secondary growth of trees, such as recurring droughts over the past 2,000 years that led to reduced ring-widths in ponderosa pine in New Mexico (Grissino-Mayer 1996). Other examples are the recurring pattern of ring-widths in bigcone Douglas-fir (*Pseudotsuga macrocarpa*; Biondi *et al.*, 2001), mountain hemlock (*Tsuga mertensiana*; Peterson and Peterson 2001) and subalpine fir (Abies lasiocarpa; Peterson et al. 2002) that correlate with PDO for up to 400 years in the past. Vegetation-type conversions from meadow to forest, changes in species growth rates and crown morphology, and changes in forest density were associated with PDO cycles in conifer forests of the Sierra Nevada, California (Millar *et al.*, 2004).

In perspective, a key characteristic of Quaternary paleoecology for the past million years is that each plant species responds to specific climatic cues with its own unique rate and sensitivity. Individual species follow their own ecological trajectories as climates cycle, leading to changes in community compositions that themselves form, dissolve, and may reform over time. Often non-analog communities (that is, species combinations that do not exist currently) have formed. From this perspective, plant communities exist as transient assemblages; species move individually through time and space following favorable climates and environments.

Implications of Natural Climate Change for Vegetation Ecology

This brief background of natural climate cycling and its effects on vegetation provides insights into concepts of forest dynamics and vegetation ecology. We offer a few examples below.

Sustainability

Ecological sustainability is a dominant operating paradigm for forest management. It implies the endurance of species, communities, and ecosystems over time, and is often used as implicit or explicit forest management and restoration goals (e.g., Jordon *et al.*, 1990, Lele and Norgaard 1996). In practice, sustainability has been difficult to describe or to recognize. Generally, it is ac-

cepted to exist when natural species diversity is maintained, species are abundantly distributed throughout their recent historic native range, community associations are maintained, natural processes occur at reference intervals and conditions, and human disturbance is minimized (Lackey 1995, Hunter 1996).

The complex and recurring cycles of ecological change in response to climate cycling challenge this interpretation of ecological sustainability. Species ranges have, and will — even in the absence of human influence — shift naturally and individualistically over small to large distances as species follow, and attempt to equilibrate with, changes in climate. In the course of adjustment, plant demography, dominance and abundance levels change, as do the relationships of plant and animal species in local communities.

A major conclusion from past records is that, at scales from years to millennia, ecological conditions are not in equilibrium, do not remain stable, nor are they sustained, but, by contrast, are in ongoing state of change (Jackson and Overpeck 2000). Paleorecords challenge interpretations of ecological sustainability that have emphasized persistence of species and stability of communities within current ranges. As widely used, such concepts of sustainability do not adequately accommodate natural dynamics, and promote misinterpretations about the behavior of natural systems.

It is important to note that the time scales under discussion are short relative to the lifespans of most existing plant species. Many native North American plant species originated 20 to 40 million years ago, and thus have been subjected to the demands of shifting climates, at both large scales and small, throughout their histories. This implies that adaptation to abrupt climate changes has had many opportunities to evolve. Resilience and sustainability, at least in terms of species persistence, appear to have been met through the capacity of plants to track favorable environments as they shift over time, and through adjustment in range distribution, habitat, associates, and population characteristics.

Population Size, Population Abundance, and Native Species Range

Changes in population size and abundance, and in overall range – observed through monitoring or other measures – are often assumed to be human-induced, whereas these may be natural species responses to climate change. For instance, species of oak (*Quercus*) and juniper (*Juniperus*) expand and contract in complementary fashion: oak population and range distribution expanded repeatedly during warm climates and contracted during cool climates while the opposite occurred for juniper species (Adam and West 1983, Heusser 1995). Although oaks in general are widespread and common in southern Oregon and California now, during repeated long glacial periods they were rare in the region. Although these changes are most obvious between long-term glacial and interglacial times, significant changes in abundance occur at climate scales as short as a decade (Heusser and Sirocko 1997).

This perspective of vegetation dynamics over the past million years compels us to evaluate causes for changes in population size, abundance, and native range more carefully. Rather than interpreting change as resulting from undesired human-induced threat, we might investigate instead whether these are natural species adaptations. For instance, *Juniperus* expanding in Great Basin rangelands has been considered an exotic invasive, and measures have been taken to remove plants. However, this expansion appears to be an adaptive response to climate change (Nowak *et al.*, 1994). Other things being equal, an ecologically-informed resource management action might be to encourage and not thwart juniper expansion.

Although changes in population size and distribution may be natural responses to climate change, causes are often difficult to discern in practice. Lags in adjustment and other imbalances between population distributions and climate mean that population changes may not be synchronous with climate change, especially when rapid climate changes occur over short times, making the search for mechanistic causes difficult (Jackson and

Overpeck 2000). Because individual plants, unlike animals, cannot "pick up and move," they migrate by dying in some areas while expanding in others. These may appear poorly segregated on the landscape – with patchiness and irregularity characteristic – making the effects difficult to evaluate while they're happening. Causes may be attributed readily to other proximal factors, such as to insects and pathogens, or human-induced effects such as fire suppression, even where climate is the underlying, ultimate factor.

A challenging question for vegetation ecology becomes, "what is the native range of a species?" The native range is the basis for monitoring its condition, understanding favorable habitat and ecological interactions, diagnosing threats and risks, determining restoration targets, and indicting species as "exotic" (Jackson 1997). Viewed against historic changes in distribution and natural flux, the native range of a species must be considered a transient and dynamic process itself, readily capable of moving in space as climate shifts over the landscape.

Population abundances and species' distribution ranges may be relatively stable whenever climate is in a more stable phase, or if the environment of a species offers considerable local diversity (Thompson 1988, Jackson and Overpeck 2000). In these cases, shifts in climate may be tracked with relatively minor overall geographic changes.

By contrast, in situations that are sensitive to change, for instance landscapes with little topographic diversity, even small shifts in climate may bring large changes in population condition. Given that the 20th and 21st centuries are undergoing rapid change in climate with high variability, we would expect population demographics and species ranges to be now highly unstable.

Reference Conditions and Restoration Targets

"Pre-disturbance" or "pre-EuroAmerican impact" conditions are used routinely as reference models and descriptions of desired targets for ecological restoration. This assumes, however, that climate

hasn't changed between the historic target time and the present.

In western North America, the disturbance period is regularly assumed to start at European/Asian contact with native peoples and their landscape, about 1840-1860, and the centuries prior are used as pre-disturbance reference conditions. As that period coincides with the coldest part of the Little Ice Age, however, it makes a poor model for 21st century restoration. Even in eastern North America, where European contact with the landscape was several centuries earlier, the dominant climate was Little Ice Age, with ecological conditions very different from present. Although "pre-modern contact" times differ around the world, the point remains: because of climate change, historic conditions are likely to be very different from present, and thus poor models for forest management or restoration.

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 1,000 years, the amplitude of natural temperature cycles has been about +/- 2°F from the average of the mid-20th century. It was 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 do humans begin to influence the climate system and global warming?

The Global Perspective

In 1988, 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, with a 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 1,000 years?* Answers to the first question came from compilations of instrumental data across earth's surface and indicate a temperature increase of 1.3°F over the 20th century (*Figure 9,* IPCC 2001). Temperature increase relative to the past 1,000 years has resulted in a number of interpretations depending on the nature of the climate indicator (such as tree rings, corals, ice cores, etc.) and the statistical interpretation. The global average
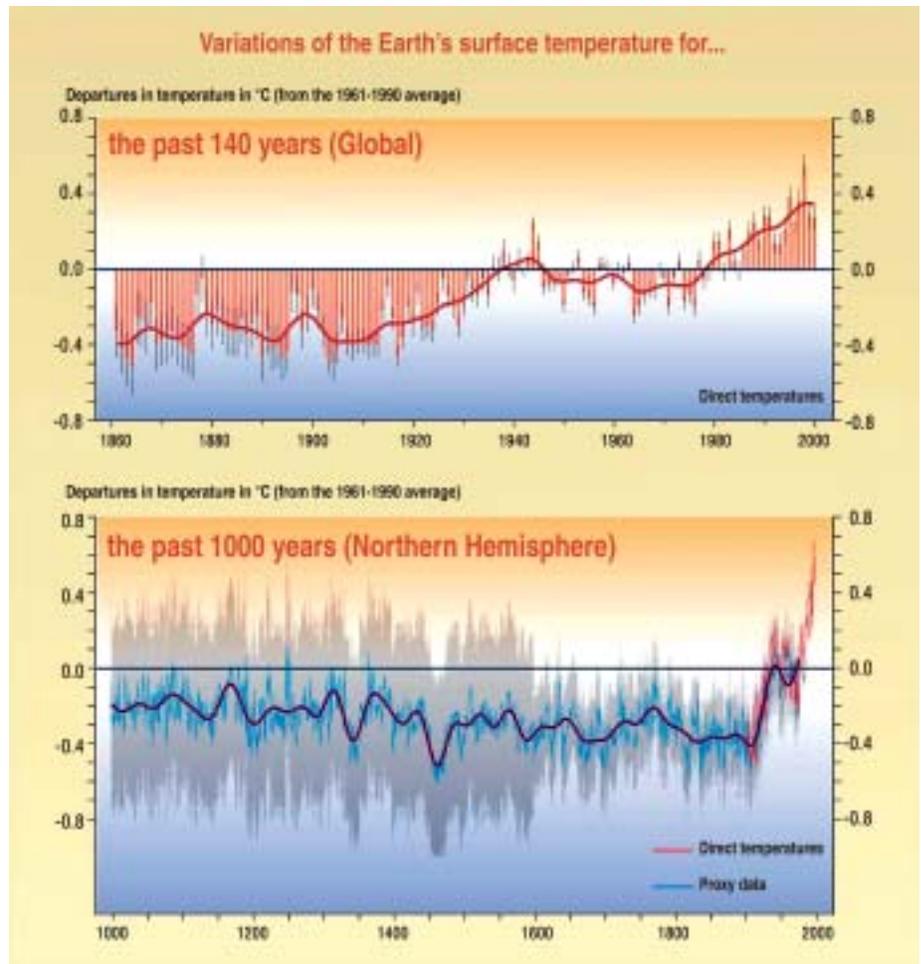
Figure 9

Global mean surface air temperature changes (°C) over the past 140 and 1000 years. From IPCC, 2001.

temperature in the late 20th century was higher than global averages over the last 1,000 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 human-induced greenhouse gas emissions (carbon dioxide, methane 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 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 depict a global average temperature increase of approximately 2.7 to 10.4°F by 2100 (*Figure 10*) and a range in CO_2 concentrations of 575 to 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 affecting the success of unwanted invasive species (Ziaska 2003), and increasing acidification of oceans with cascading effects on ocean biota. The role of increased efficiency of photosynthesis by plants has been touted as beneficial for the fertilizing effect on tree growth and changes in water-use efficiency. 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
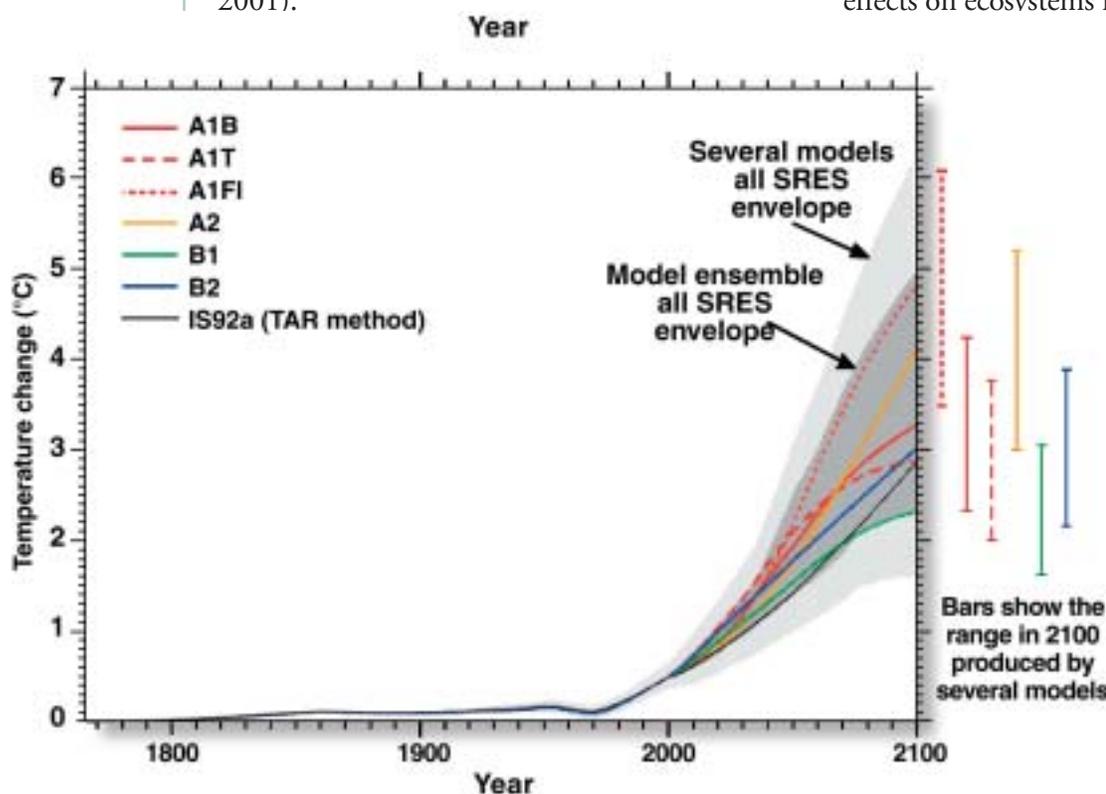

Figure 10   **Global mean surface air temperatures (°C) projected for the 21st century** and plotted with the observed temperature trend prior to 2001. Multiple lines after 2100 indicate different results from climate models; bars show ranges for each model. From IPCC, 2001.

stems, roots, or fruits. Old-growth forests may respond less than young trees, and all forests studied 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 (surface reflectance) 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 approximately 50% decline over the western U.S. during the 20th century, Mennis and Fountain 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" (i.e., increases in density) of temperate lowland and montane forests, followed by "browning down" (mortality) as a result of epic forest dieback and uncharacteristically severe wildfires (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 time required for the climate system to equilibrate reductions in CO_2. Assuming greenhouse gas 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 to 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 greenhouse gas emissions; if they are not controlled, climate changes will be significantly amplified. The effects of human-caused emissions on climate,

combined with land-use changes that affect climate, give rise to the recognition that a human-dominated climate system is characteristic of the new millennium.

Potential Impacts of Climate Change on Oregon Ecosystems

The potential future impacts of climate change on ecosystems in the Northwest have been estimated using a variety of climate and vegetation models. Following are new estimates that build upon earlier work that contributed to a National Assessment of the potential impacts of climate change, which was sponsored by the U.S. Global Change Research Program (Bachelet *et al.*, 2001).
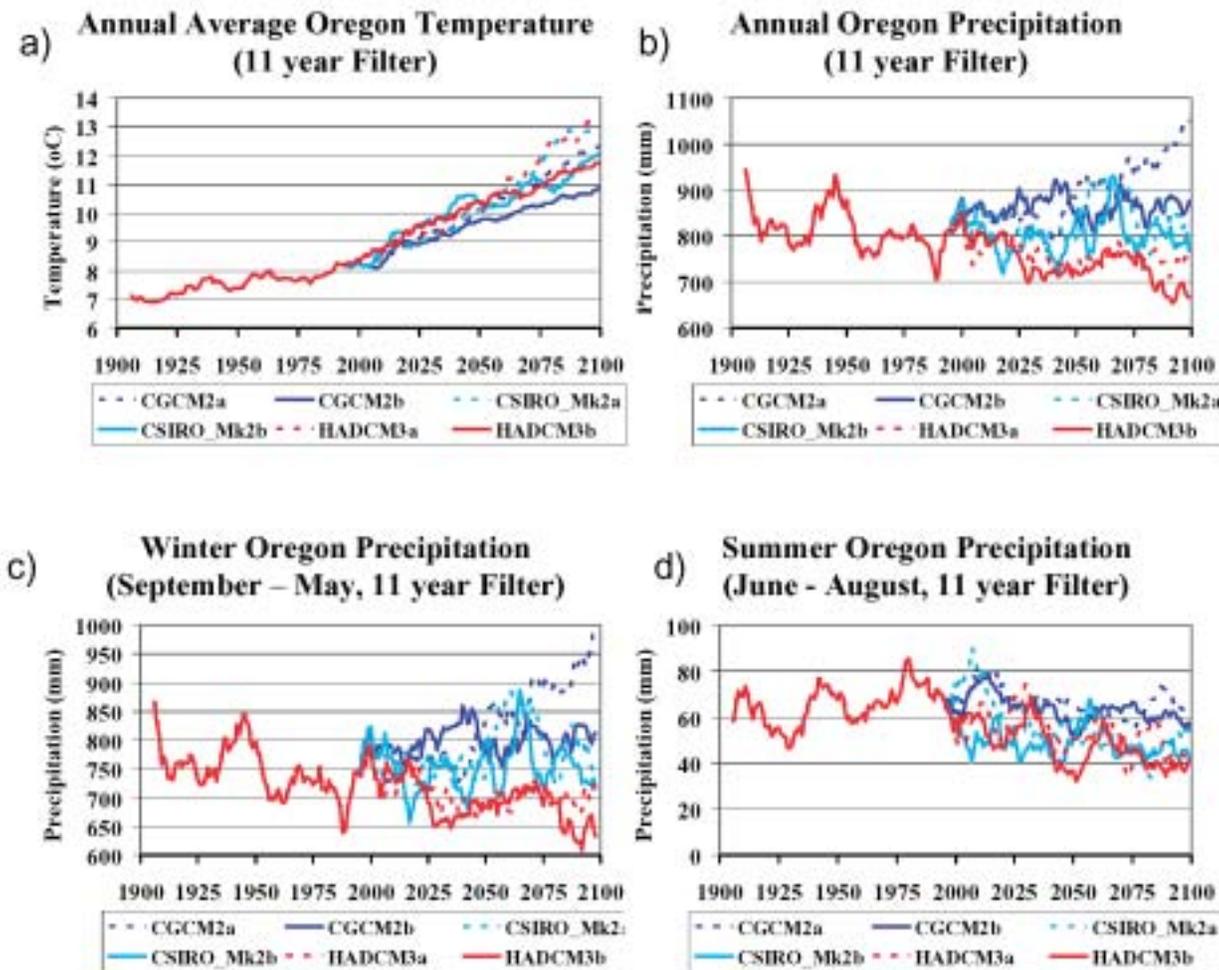
Temperature and Precipitation

The future climate scenarios presented here use three general circulation models, coupled with dynamic ocean models, each simulating two IPCC greenhouse gas emissions scenarios through the 21st century, moderately high (A2) and moderately low (B2).[1] The three global climate models were developed in Canada (CGCM2), the United Kingdom (HADCM3), and Australia (CSIRO).

The scenarios show temperature across Oregon increasing from the present time to the end of the 21st century from about 7 to 8 °F, which can lengthen the growing season by at least four to six weeks (*Figure 11*). For precipitation, the scenarios show a range in winter of 10% decrease to 24% increase, but decreases of 10 to 40 % in summer (a relatively small amount since summers are generally dry). The potential winter decrease is important because previous studies had shown significant *increases* in Northwest precipitation (NAST 2000).

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[1] *Intergovernmental Panel on Climate Change, Special Report on Emissions Scenarios, IPCC SRES A2 and B2 were used in a new and ongoing assessment of the impacts of climate change over North America (Price et al., 2004).*

The VINCERA Project

A new class of ecosystem model called DGVMs, or *Dynamic General Vegetation Models*, combines additional types of data for improved forecasts of projected climate changes on natural ecosystems. These new models combine two traditionally separate fields within ecology — the distribution of vegetation, and biogeochemical cycling (how nutrient cycling affects plant productivity). In addition, DGVMs also include a third element, wildfire simulation, which can be a large component of the flux of carbon back to the atmosphere.

Three Dynamic General Vegetation Models — simulating changes in vegetation distribution, carbon balance, and disturbances from drought and fire — were analyzed more broadly in a project known as VINCERA, *Vulnerability and Impacts of North American Forests to Climate Change: Ecosystem Responses and Adaptation.*

Results from one of these vegetation models, MC1 (MAPSS-CENTURY, version 1), are presented here.

a. Impacts of Climate on Future Distribution of Vegetation

Figure 12 shows Observed (current) vegetation for the Northwest, compared with two simulations under Historical Climate (1961 to 1990, with and without fire suppression) and six scenarios of Future Vegetation Distribution simulated for the end of the 21st century (2070 to 2099). This figure depicts six future climate scenarios developed by the three climate modeling groups, each using two different assumptions of future greenhouse gas emissions (A2, medium high; B2, medium low).

The two historical simulations are reasonable renditions of the observed current natural

vegetation distribution. The apparent overabundance of boreal forest (blue) is not a major problem, since the boreal trees are functionally very similar to the temperate conifer forest shown in the observed map. The historical simulations demonstrate the effect of fire suppression, implemented in the model in 1950, on the expansion of woodlands and savannas (juniper and ponderosa pine) into the sagebrush vegetation in eastern Oregon in recent decades. This is a well-described phenomenon and is currently threatening numerous sagebrush habitats for wildlife.

The simulations of future vegetation distribution include no fire suppression and yet in all scenarios, the interior shrublands/grasslands are overtaken by expansion of woodlands (e.g. juniper), savannas (e.g. Ponderosa pine), or continental conifer forests (e.g. Douglas-fir), due to increases in precipitation, enhanced water use efficiency from elevated CO_2 and a lengthened growing season. The maritime forests along the wet coastal regions are displaced in many future climate scenarios by the "warm temperate-subtropical mixed forest," or the interior conifer forests. Overall, there is an increase in broadleaf vegetation amidst the conifer forests, both along the coast and inland, suggesting expansions of species such as alder, maple, madrone, oak, pines and other Klamath region and California species.
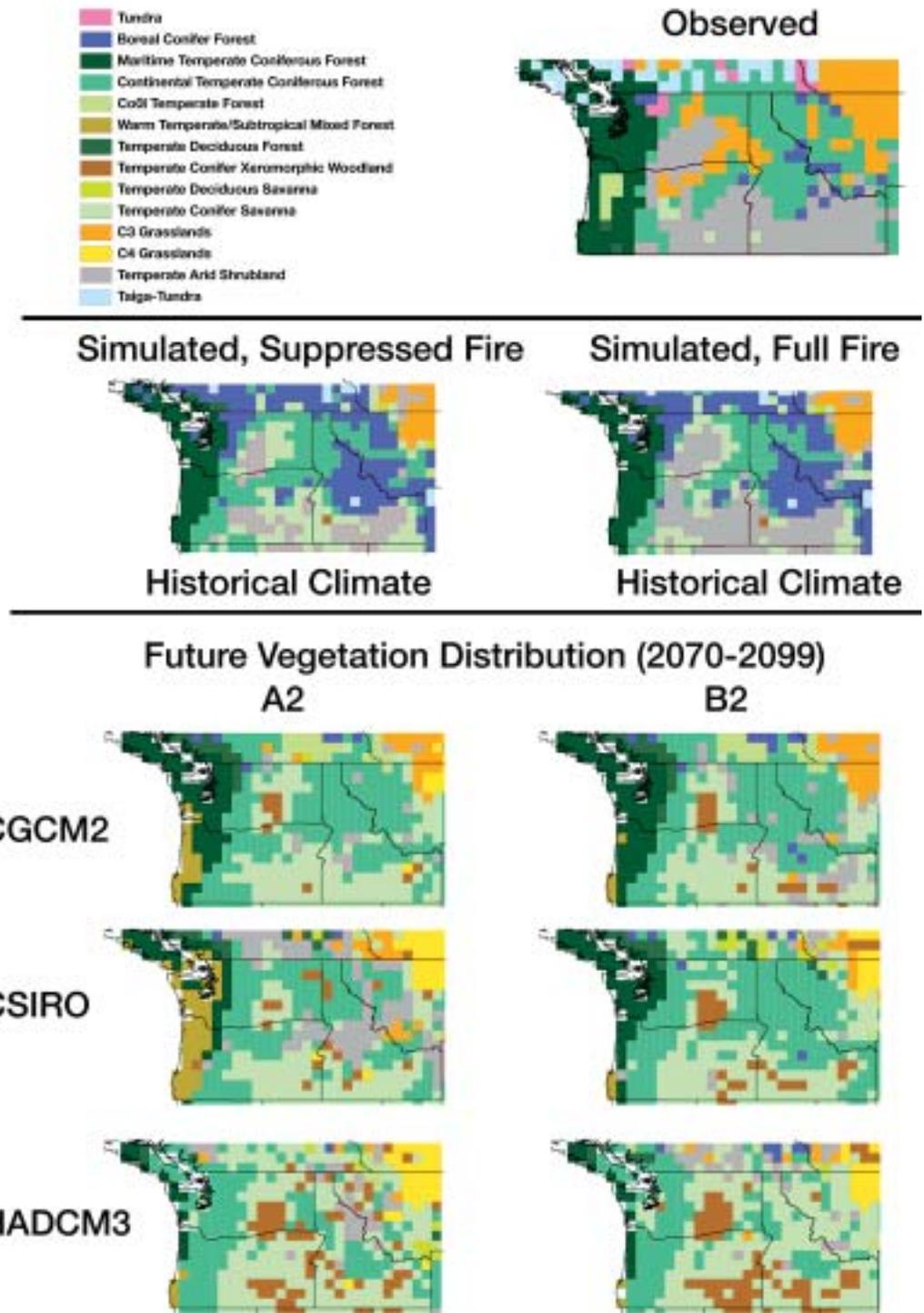
Figure 12

Vegetation distribution. Observed, simulated historical and future vegetation distribution. The two historical simulations (with and without fire suppression) show a reasonable comparison to the 'observed' current vegetation distribution. The primary features to note are the maritime forests along the wet coastal regions (dark green) and the interior, dry sagebrush regions (gray). The maritime forests are displaced in many future climate scenarios by the 'Warm Temperate-Subtropical Mixed forest', or the interior conifer forests. In all scenarios, the interior shrublands/grasslands are overtaken by expansion of woodlands (e.g. Juniper), savannas (e.g. Ponderosa Pine), or continental conifer forests (e.g. Douglas-fir). *See text for further details.*

b. Impacts of Fire on Future Distribution of Vegetation

Figure 13 shows future climate scenarios with percent change in biome area in Oregon, without (13a) and with (13b) fire suppression.

Percent Change in Biome Area

The fourteen vegetation types shown in *Figure 12* were aggregated into four vegetation classes (*Table 1*).

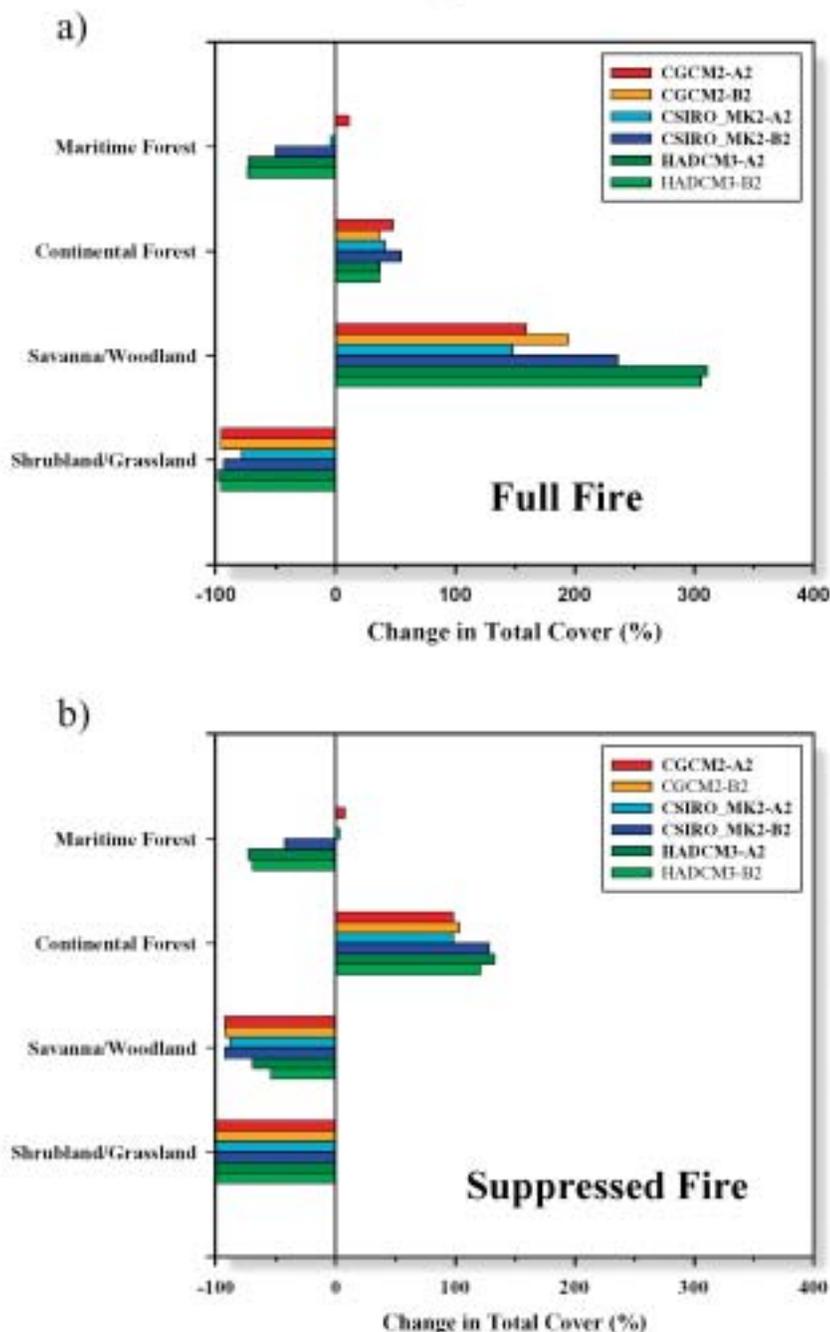With **Full Fire** across all six scenarios (*Figure 13a*), **maritime forest** either increased in area slightly by about 12%, or showed a range of decreases in area from nil to over 70%. The maritime forests were displaced either by the warm temperate/subtropical mixed forest or the continental temperate forest. The former carries more broadleaf species such as oak and madrone whereas the latter is typified more by Douglas-fir and both types are accustomed to more fire. With suppressed fire **continental forest** increased in area by about 40% to nearly 60%; while, **savanna/woodland** increased by about 150% to over 300%, as they both encroached upon the drier shrub and grasslands. Shrubland/grassland showed decreases in area from about 80% to over 90%. (*Figure 13a*).

In contrast, with **Suppressed Fire** (*Figure 13b*), **continental forest** increased even more, as it took over the role of **savanna/woodland** in displacing **shrubland/grassland**, which disappeared entirely, being largely replaced by the continental forest.

The simulated future distribution of vegetation, shows a significant increase in woody vegetation in the interior dry ecosystems (*Figure 12*). With increases in temperature, there would be significant reductions in alpine vegetation, as the upper treeline moves upward in elevation, as shown in previous higher resolution simulations (Bachelet *et al.*, 2001). The simulations show some increase in warm temperate/subtropical mixed forest in the coastal mountains of both Oregon and Washington. This implies an increase in broadleaf deciduous and evergreen species, perhaps such as present in the Klamath region with madrone, tanoak and other oak species in the drier sites, and maple and alder in the wetter sites. More southerly conifers could also be favored, such as possibly redwood or

Figure 13   **Percent change in biome area in Oregon,** without and with fire suppression, under six future climate scenarios, comparing (2070 – 2099) with (1961 – 1990). The 14 different vegetation classes shown in Figure 12 have been aggregated to four major biome types. See Table 1 for definitions of biomes.

Table 1.

MC1 vegetation type aggregation scheme and regional examples of the vegetation classes

Vegetation Class	Vegetation Type	Regional Examples
Maritime Forest	**Maritime Temperate Conifer Forest Cool Temperate Mixed Forest Warm Temperate/Subtropical Mixed Forest Temperate Deciduous Forest**	**Sitka Spruce – Western Red Cedar – Western Hemlock - Douglas-fir Forest Alder – Maple – Oak Forests Mixed Conifer Forest Ponderosa Pine Forest Tanoak–Madrone–Oak Forest Coastal Redwood Forest**
Continental Forest	**Tundra Boreal Forest Continental Temperate Coniferous Forest**	**Alpine Meadows Aspen Subalpine Forest – True firs – Mountain Hemlock Douglas-fir – Western Hemlock Forest**
Savanna / Woodland	**Temperate Conifer Savanna Temperate Conifer Xeromorphic Woodland**	**Yellow Pine Savanna Douglas-fir–Tanoak Savanna Mixed Conifer Savanna**
Shrubland / Grassland	**Temperate Arid Shrubland C3 Grassland C4 Grassland**	**Sagebrush Steppe Palouse**

even some pines. However, slow migratory rates of southerly (California) species would likely limit their presence in Oregon through the 21st century (Neilson *et al.*, 2005). The drier interior vegetation shows a large increase in savanna/woodland types, suggesting possibly juniper and yellow pine species range expansions. Also, if winter temperatures warm sufficiently, then hard frosts could become less frequent and open the door to an entire flora of frost-sensitive species from the Southwest potentially displacing many native eastern Oregon species over the course of decades to centuries (Neilson *et al.*, in press).

Hotter temperatures would enhance evaporative demand, tending to drought-stress the vegetation. However, that is somewhat countered, or even reversed, if it is also accompanied by increases in precipitation, as well as the increased water use efficiency of the vegetation from elevated CO_2 concentrations.

Decreases in summer precipitation, accompanied by a longer growing season, would tend to increase the drought stress. However, the future scenarios show an increase in winter precipitation. There is speculation that as global oceans warm, the world could shift into a more positive PDO regime, similar to an extended El Niño (Mote *et al.*, 2003). These conditions often shift storms away from the Northwest, creating dry conditions.

Fire increases significantly in the coast range and Willamette Valley in Oregon in the absence
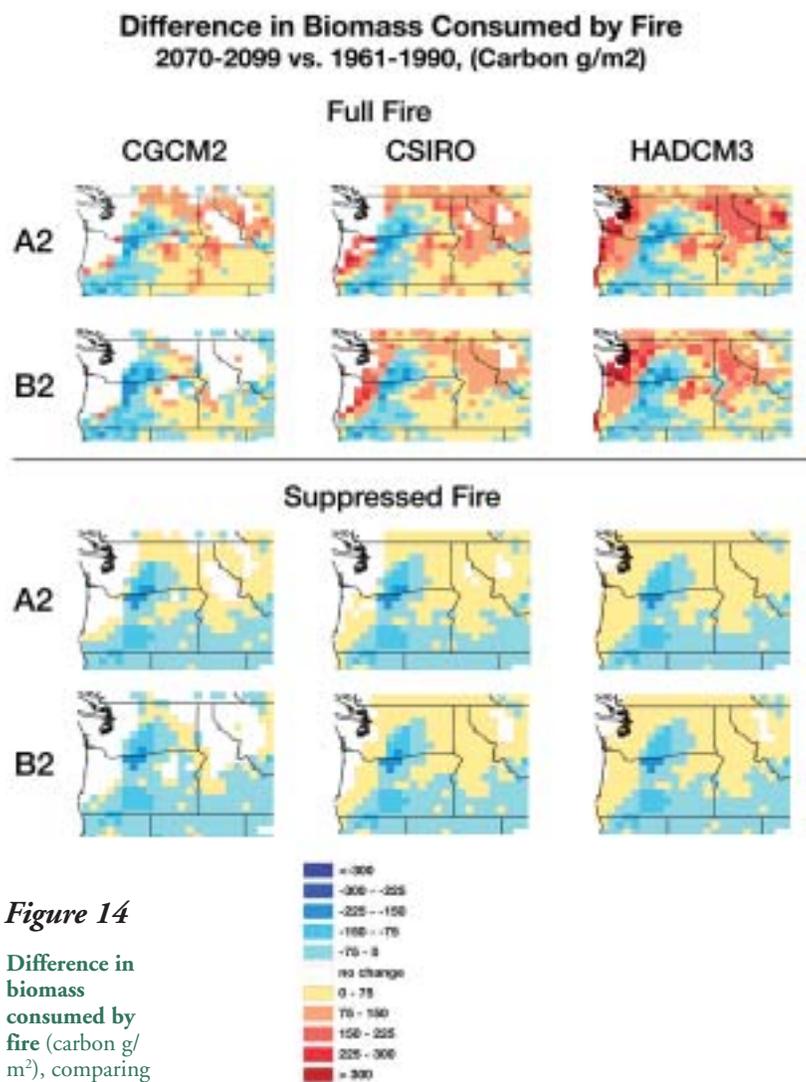
Difference in Biomass Consumed by Fire
2070-2099 vs. 1961-1990, (Carbon g/m2)

Full Fire

Figure 14

Difference in biomass consumed by fire (carbon g/m²), comparing the future average ecosystem biomass consumed by fire (2070 – 2099) with the current (1961 – 1990) biomass consumed, without fire suppression (upper panel) and with fire suppression (lower panel). The six future scenarios are arrayed by GCM (columns) and emissions scenarios (rows). The GCM definitions are as in Figure 11.

c. Extended Growing Season

The increases in temperature would advance the onset of spring growth, bringing it closer in line with the spring precipitation peak that is characteristic of the Northwest. Most of the vegetation growth is accomplished in the spring, before the long, dry summer. However, Northwest vegetation, particularly in the drier interior, tends to be deeply rooted and can take advantage of the winter rains for persistence throughout the summer, due to the winter and spring recharge of the deep soil layers.

Even though the percentage decreases in summer rainfall are large, the summers are generally dry in any case, so the absolute magnitude of the change is not as great as it seems. The effects of increased summer temperatures on evaporative demand are likely of greater importance. However, since the growing season would be longer on both spring and fall ends, the vegetation would demand more water overall, unless the impact of elevated CO_2 concentrations on water use efficiency and the increased winter precipitation are sufficient to offset the demand.

It is not easy to anticipate whether, for example, the sagebrush ecosystem would increase or decrease in certain domains in the Northwest, as illustrated in Figure 12, since there are so many counter-acting forces. The overall changes in area of the different aggregated ecosystems, specifically for Oregon, simplify the complex changes expressed in the maps and are shown in *Figure 13*. The shrubland/grassland vegetation type decreases due to woody encroachment. The lengthening of the growing season is especially important in the interior dry ecosystems, where the traditionally very cold winters prevent significant photosynthesis until late spring when the rains are typically waning. Thus, even with the drier scenarios, the interior vegetation can much more effectively utilize the winter precipitation.

of fire suppression in all scenarios, especially the drier Hadley (HADCM3) and Australian (CSIRO) scenarios (*Figure 15*). The Willamette Valley and east slopes of the coast range appear to be most at risk of increased fire. Much of this increase in fire can be mitigated by fire suppression, but would likely require significant mobilization of fire fighting resources above current levels

However, the coastal forests are heavily managed and have a very complex harvest history and age-class structure. Much of the region is recovering from clear-cut logging and is likely still below the water-limited carrying capacity and may yet be in a position to benefit from the warmer winters and elevated CO_2. These younger ecosystems, with lower stature and less "rough" canopies, may use less water and be less likely to experience drought stress followed by fire.

The greater the effectiveness of fire suppression, the greater will be the woody expansion, even moving toward a closed canopy in many regions of the interior (*Figure 13*). The effect of the delicate balance between all the contrasting forces can best be observed in the changes in vegetation and ecosystem carbon and on whether fire consumes more or less biomass.

d) Change in Vegetation Carbon

With climate change, the wet maritime forests tend to lose carbon, even under scenarios with increased precipitation, (Figure 15). Interior dry ecosystems tend to gain carbon. The interior conifer forests lose carbon without fire suppression, but gain carbon with fire suppression. The wet maritime forests are unique among Northwest ecosystems in that the historical fire return interval is sufficiently long that the simulated ecosystems have grown up to their water-limited carrying capacity. Thus, the increases in temperature lengthen the effective growing season of the maritime forest, as well as produce a much higher evaporative demand. The result is that the trees, with their current leaf area, withdraw more water during the hot summer than is available in the soil. Therefore, the leaf area is reduced via dieback of leaves, branches and trees, augmented in some cases by increases in fire   With a lower leaf area, implying a less dense forest (as shown by the reduced vegetation carbon), the forest is again able to maintain a positive water balance throughout the summer.

The interior forests show an increase in leaf area under the future climate, due to a more favorable synchrony between their growing season and the precipitation, and are also normally maintained by fire at a lower leaf area than could be maintained by the water balance. The increase in the vegetation density in these interior ecosystems is also driven by increases in winter precipitation and enhanced water use efficiency from elevated CO_2. The interior savanna/woodland ecosystems are able to put on more biomass even with an increase in fire and without fire suppression. However, the

Percent Change in Vegetation Carbon
2070-2099 vs. 1961-1990

Figure 15

Percent change in vegetation carbon, comparing the future average ecosystem carbon density (2070 – 2099) with current (1961 – 1990) carbon density, without fire suppression (upper panel) and with fire suppression (lower panel). The six future scenarios are arrayed by GCM (columns) and emissions scenarios (rows). The GCM definitions are as in Figure 11.

presence or absence of fire suppression serves to modulate whether the interior conifer forest ecosystems become carbon sources or sinks (*Figures 14, 15*).

Summary

With climate change, all ecosystems in the Northwest show significant changes in species composition, fire disturbance and carbon balance. The complexities and nuances of counteracting forces cannot be minimized. Even with the newest modeling techniques, the balances in the real world are difficult to forecast. However, colder ecosystems (alpine) will be threatened while warmer ecosystems will increase. Fire is likely to increase, even in wet coastal ecosystems. Ecosystem carbon gains and losses will be mixed, but fire suppression or exclusion could have a profound positive influence on ecosystem carbon sequestration.

Forest Management in the Face of Changing Climates

In the context of changing climates and increasing atmospheric carbon, basic concepts and overall strategies frame the discussion. These can be categorized as *mitigation, adaptation*, and *conservation*. Mitigation practices aim to reduce emissions of new greenhouse gases, as well as to remove existing CO_2 from the atmosphere. Adaptation practices include actions to increase the capacity of forests, 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 forests, ecosystems, and ecosystem services. For forest management to meet these three principles, we outline five decision-making strategies. They are *Reduce* Greenhouse Gases, *Resist* Change, Create *Resilience* After Disturbance, *Respond* to Change, and Conduct *Triage* (Millar 2006). 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.

(1) 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 human-induced climate and atmospheric effects by reducing greenhouse gas 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 Oregon are taking steps to establish standards that compare to

Kyoto-protocol countries. These fall under the category of sequestering greenhouses gases, reducing unnecessary emissions, and maintaining a "house in order."

Sequester Greenhouse Gases. Plants remove CO_2 from the atmosphere 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 below-ground 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. This process can be exploited as a mitigation strategy.

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 Oregon, Washington, and California," (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. 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.

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 greenhouse gas emissions by reducing fire vulnerabilities but provides alternative energy to replace fossil-fuel and other high greenhouse gas-emitting forms of energy.

Reduce Unnecessary Emissions. Wildfire and extensive forest mortality as a result of insect and disease are primary sources of unintentional carbon emissions from forests in western U.S., and represent 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). 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, results in prep).

Management practices that lower forest vulnerabilities to wildfire and non-fire mortality should 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. For example, 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 greenhouse gas 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.

(2) 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 Oregon, 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 are important. This applies to invasive plants, animals (vertebrate and invertebrates), and pathogens. 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.

(3) 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, and retaining resiliency will become more difficult as changes in climate accelerate.

(4) Respond to Climate Change.

Another 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. 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. Use coupled and downscaled climate and vegetation models to anticipate future regional conditions and project future forest stands and plantations into new habitat and climate space.

Anticipate and Plan for Indirect Effects. Evaluate potential for indirect effects, such as changes in fire regimes and exotic insects and pathogen

responses, and plan management accordingly.

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, bet-hedging practices may be a better choice. Essentially this group of actions plans for uncertainty in the future rather than a certain (modeled) scenario, and promotes decisions that spread risk rather than concentrating it.

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 bet-hedging practice.

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).

Experiment with Refugia. Plant ecologists and paleoecologists recognize that some environments 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.

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). 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.

(5) 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. 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, and forms the context against which current human effects on climate can be evaluated. Natural cycles in climates occur at millennial, century, decadal, and interannual time frames. Climate states may shift abruptly over times as short as years or decades. Over historic time, species have adapted to climate changes by shifting ranges and (over long time spans) adapting through genetic change. Since the 1970s, the interaction of climate-driving mechanisms has shifted to become dominated by anthropogenic influence, predominantly greenhouse gas 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 Oregon's climate future suggest warming temperatures by 7 to 8.5°F and somewhat 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. Significant shifts in forest, shrub, and grasslands, as well as fire regimes, are anticipated.

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 smaller and more adaptable 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 to 100 years must be a period when greenhouse gas 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, forest managers can help to mitigate ongoing climate changes and greenhouse gas emissions, plan strategies to adapt to change, and take actions to conserve energy use and relieve stress on ecosystems.

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