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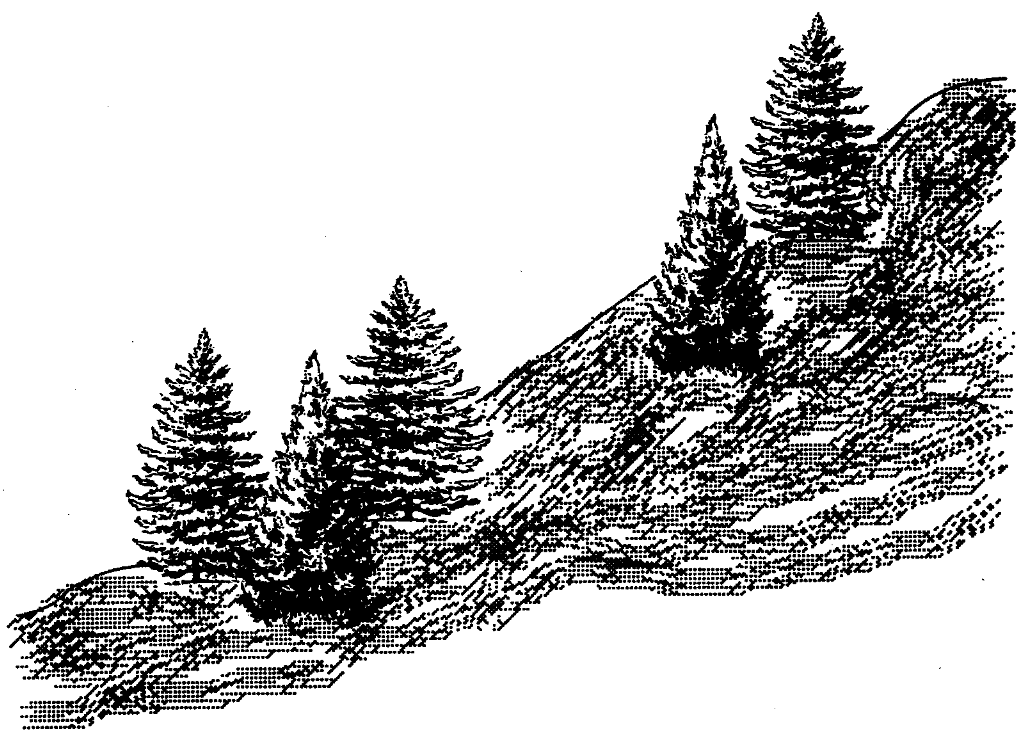

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# POTENTIAL IMPACTS OF CLIMATE CHANGE ON PACIFIC NORTHWEST FOREST VEGETATION

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## FINDINGS

The continued accumulation of radiatively-active trace gases in the atmosphere may significantly alter the climate of the Pacific Northwest. Mean annual temperatures could increase 2° to 5°C. The seasonality of precipitation will likely remain the same, but with annual totals remaining unchanged or increasing 20%.

The potential effects of these climate changes on Northwest forests have been estimated using a variety of modeling approaches and climate scenarios. Overall, 26 to 90% of the area in the Northwest may change from one general vegetation type to another. Forest area in the Northwest could decrease 5 to 25%. Remaining forest land would differ in species composition, and likely be less productive than current forests. In Oregon, drier Douglas-fir dominated forests would increase in area, whereas the more productive western hemlock - Douglas-fir forests would decrease. Forest vegetation zones would rise in elevation from 500 to 1000m. Alpine and subalpine forests could disappear from all but the highest elevations in the region.

Detrital carbon stores in the Oregon Cascades could be reduced by as much as 30% with a 5°C climate warming. Assuming no change in forest productivity, there could be a net loss of 60 Mg of carbon per hectare from the same region. This compares to a decrease in carbon storage of 305-370 Mg per hectare resulting from conversion of old growth forests to young plantations.

Forest disturbances such as fire, wind and pest/pathogen outbreaks will likely increase in frequency, speeding vegetation change in response to climate change. Disturbances imposed on forests through timber management practices may also hasten the response of forests to climate change. Also, current management practices coupled with natural disturbances may inhibit establishment of new forests at the same time as older forests are changing.

There are two key limitations to the data presented here. First, the transient (time-dependent) dynamics of change have not been adequately investigated. How forests respond to a rapidly changing but variable climate is uncertain. Second, the direct effects of enhanced $CO_2$ concentrations on forest species growth have not been considered in any of the modeling simulations. Laboratory experiments suggest the potential for increased drought tolerance by individual plants under higher $CO_2$ concentrations. The landscape scale impacts of higher $CO_2$ concentrations on vegetation and water balance are uncertain.

In sum, natural and human caused disturbances of the landscape will play a major role in the response of regional forests to climate change. The interplay of forest management and natural forest processes needs to be considered in future assessments of climate change impacts on Northwest forests. They also must be considered in designing mitigation options for reducing the impact of climate change on regional forests.

Forest managers are thus presented with a difficult problem. How should current forests be managed given 1) our uncertainty of the magnitude and direction of future climate change and 2) the potential for large changes in forest composition and distribution if the climate does change as currently simulated by state-of-the-art climate models?

## INTRODUCTION

The forests of the northwestern United States are dominated by evergreen conifers that are long-lived and grow to sizes unmatched in other parts of the world (Waring and Franklin 1979, Franklin 1988). These forests are unique among north temperate forest types. Biomass storage is also higher than any other vegetation type in the world (Waring and Franklin 1979, Franklin 1988, Harmon et al. 1990). Besides their intrinsic value as unique ecological systems, Northwest forests serve as an important source of timber and are a focus of the regional tourism industry. The potential for significant changes in the regional climate caused by global increases in radiatively important trace gases (IPCC 1990) has raised concern over the future of Northwest forests. The purpose of this paper is to summarize current understanding of the potential effects of climate change on this important regional resource. We will focus on the forests in Washington and Oregon, with some results and analysis applicable in the state of Idaho.

## CURRENT STATUS OF NORTHWEST FORESTS

### Common Forest Types

Forests occupy 72 million acres in Washington, Oregon, and Idaho, or about 46% of the region (Fig. 1). The distribution of forests is discontinuous across the region. Forests dominate the land west of the Cascades and occupy higher elevations east of the Cascades and in the Northern Rocky Mountains in Idaho. Great Basin Steppe vegetation occupies the lowlands between the Rocky Mountains and the Cascade range (Kuchler 1964, USDA 1970).

West of the Cascade crest in Washington and Oregon four major forest zones have been described (Franklin and Dyrness 1988). Along the Pacific coast, a narrow band of Sitka spruce and western hemlock forest prevails (see Table 1 for scientific nomenclature of common species in the region). Sitka spruce is only found within a few tens of kilometers of the coast, forming pure stands adjacent to the coast (or with lodgepole pine) because of its salt tolerance. Throughout the zone western hemlock is usually more abundant than sitka spruce (Franklin 1988).

The western hemlock zone occupies most of the land between the Sitka spruce zone and higher elevational zones in the Washington and Oregon Cascades (Franklin and Dyrness 1988). This zone is essentially equivalent to the Douglas-fir zone of the Society of American Foresters (SAF) vegetation classification (USDA 1970; Fig. 1). Most of the timber production in the region is concentrated in this zone. Western hemlock is the dominant climax species, while Douglas-fir is an important successional tree species. However, Douglas-fir can be a common tree in older forests, as can western red cedar. Within the western hemlock zone, six major associations have been identified along a moisture gradient. The Douglas-fir series occurs on drier sites. On moister sites, western hemlock increases in importance and is a key member of the other five vegetation associations. Forest productivity increases along the moisture gradient together with the change in vegetation (Gholz 1982). Carbon storage in mature Douglas-fir - western hemlock forests averages over 600 Mg/ha, while second growth 60 year old forests average 250 - 275 Mg/ha (Harmon et al. 1990).

The silver fir zone occupies elevations between the lower western hemlock zone and subalpine forests in the Cascades. Silver fir is the dominant tree, with western hemlock, noble fir, western white pine and western red cedar common associates. Subalpine forests are dominated by mountain hemlock, with subalpine fir and lodgepole pine successional species (Franklin and Dyrness 1988).

Total annual precipitation decreases rapidly east of the Cascade crest, and forests are dominated by species adapted to the drier conditions. Ponderosa pine forests form a narrow band of vegetation on the east slope of the Cascades in Oregon and southern Washington (Fig. 1). Forests with lodgepole pine as the dominant tree species are common in southern Oregon, east of the crest. Juniper woodlands occur between sagebrush steppe and ponderosa pine forests in central Oregon (Franklin and Dyrness 1988).

Idaho forests tend to be dominated at lower elevations by ponderosa pine and Douglas fir (Fig. 1; Franklin and Dyrness 1988). Grand fir, white pine, and lodgepole pine commonly occur in mid-elevational forests in northern Idaho. Upper elevations forests often consist of subalpine fir, Engelmann spruce, western hemlock, and mountain hemlock.

Two other forest types in the southern part of the Northwest deserve mention here because of the potential for their expansion in the region under warmer climatic conditions. Mixed conifer and evergreen hardwood forests are typical in the Klamath Mountains in southwestern Oregon and northern California (Whittaker 1960, Franklin 1988). Douglas-fir is usually the dominant conifer, and the evergreen-broadleaved trees tanoak, canyon live oak, Pacific madrone, and golden chinkapin can form a hardwood understory. Oak woodlands are common in interior valleys between the Oregon Cascades and Coast Range. Oregon white oak is a common tree species in these woodlands.

Forest productivity is strongly related to moisture supply. Coastal forests have a net primary productivity up to five times greater than ponderosa pine forests east of the Cascade crest, and are as productive as any other vegetation type in the world (Gholz 1982). From a timber production perspective, northwestern forests continue to accumulate biomass longer after planting than other temperate forests. For instance, a single 100 year rotation of Douglas fir produces 22% more wood than two 50 year rotations of loblolly pine in the Southeast (Worthington 1954).

Natural Forest Disturbances

"Disturbances create the conditions for change in ecosystems, effectively doing the work of eliminating established forests with its inertia, or tolerance of altered climatic conditions" (Franklin et al. 1991). Wildfires and windstorms, along with pests and pathogens, are the most important catastrophic disturbances in the Pacific Northwest forests. The locations, frequencies and intensities of these disturbances will probably increase under proposed climate scenarios because these disturbances are either linked to climate or are climatically driven.

Forest fires have had an important effect on the structure and composition of Northwest forests (e.g. Hemstrom and Franklin 1982, Teensma 1987, Morrison and Swanson 1990) and will play an important role in the response of forests to future climate change. Fire impacts on forests include maintaining early successional species in a landscape as well as increasing the diversity of stand age-classes. Fires create forest openings and thus edge environments important as habitat for certain wildlife species.

Prior to European settlement natural fire regimes in Northwest forests varied considerably depending primarily on moisture status and ignition frequency. At Mount Rainier, WA, the natural fire rotation can be as long as 400-500 years (Hemstrom and Franklin 1982). To the south at H.J. Andrews Experimental Forest, OR, drier conditions and more frequent lightning resulted in a natural fire rotation of about 80 years (Teensma 1987). Fire frequencies are typically higher in forests east of the Cascade Crest. In dry ponderosa pine forests, fire frequencies range from 10 to 15 years (Bork 1985). Natural fire rotations have decreased dramatically since the beginning of active fire suppression (Hemstrom and Franklin 1982, Teensma 1987). For instance the fire rotation at H.J. Andrews has increased to about 600 years (Teensma 1987). The decrease in fire frequency and buildup of fuels could increase the severity of future fires (Kaufmann 1990).

Wind storms can also produce widespread tree mortality, but are of lesser importance in the Cascades than along the coastal mountains. Pest and pathogen outbreaks in the Pacific Northwest forests are not as frequent as in other western conifer forests but will likely increase under climate change (Franklin 1988).

Current Land Use

About 75% of the forest land in the Northwest is managed for timber production (USDA 1990). Over the region, about 63% of the timberland is publicly owned, although in Washington State timberland is equally divided between public and private ownership. The forest industry owns about half of the private forest lands in the Northwest.

Currently timberlands are in transition from unmanaged old growth forests to managed forest plantations. Of the 7 million ha of old growth present before the turn of the century in western Washington and Oregon, five million ha has been converted to plantations (Harmon et al. 1990). In managed forests, rotation length is planned to be about 70-120 years on National Forest lands (Swanson et al. in press). Douglas-fir is preferentially replanted after clear-cutting, and the proportion of young Douglas-fir stands in the western hemlock zone has steadily increased over time (Franklin and Dyrness 1988).

Harvesting of Northwest timber has imposed a new disturbance regime on regional forests. Like forest fires, clear-cutting followed by controlled fires opens the forest canopy and prepares a seed bed favorable for tree establishment. Also, both increase forest edge habitat and significantly change the age-class distribution and successional status of forests within a landscape unit.

There are specific differences between the effects of forest fires and timber harvesting on a landscape, however. After clear-cutting, forest edges are more distinct than those produced by fires. Fires tend to leave snags, logs and a few trees along edges, whereas these tend to be removed during clear-cutting (Morrison and Swanson 1990). The abundance of competing shrubs and hardwood species is often controlled after cutting, and the subsequent forest succession is less diverse than that after a fire. In regions where clear-cutting has been particularly frequent over a period of years, the proportion of interior forest has been significantly reduced (T. Spies, personal communication, Pacific Northwest Research Laboratory, USDA Forest Service). This effectively reduces the amount of habitat available for old growth dependent species such as the spotted owl.

### Future Resource Condition Without Climate Change

Even without climate change, management of Northwest forests will face difficult challenges in the future. Society is placing increasing demands on forests for recreation, preservation of old growth forests, and maintenance of biodiversity in addition to their traditional use as a source of timber. The greatest near-term challenge will be developing a strategy to protect the northern spotted owl (USDA 1988, Thomas et al. 1990). Whatever strategy is adopted will likely reduce timber supplies in the future, while maintaining large tracts of heretofore unprotected old growth forest.

A related management challenge is to assess the environmental effects of the conversion of natural stands into managed plantations (Swanson et al. in press). A key issue is how to disperse cutting patterns on a forested landscape. The widely used practice of dispersed 10-20 ha cuts through an uncut landscape will eventually fragment the remaining forests into smaller and smaller contiguous tracts, reducing the amount of interior forest habitat (Franklin and Forman 1987). Techniques that model landscape patterns have been developed to help evaluate alternative cutting patterns (Hemstrom 1990, Cissel 1990, Swanson et al. in press). Key findings of these landscape-scale analyses are that the full impact of a management strategy may take decades to unfold, and it may take decades to change an established landscape pattern imposed under an earlier management strategy (Swanson et al. in press).

## SENSITIVITY OF FORESTS TO CURRENT AND FUTURE CLIMATE

### Current Climate

"Climatically the [Pacific Northwest] region experiences wet-mild winters and warm-dry summers. The dormant season, when shoot growth is inactive, is characterized by heavy precipitation with daytime temperatures usually above freezing. Away from the coast, the growing season is characterized by warm temperatures, clear days, and little precipitation. Water storage in snowpack, soils and vegetation - as well as pulses of fog, clouds, or cool maritime air which reduce evapotranspiration - obviously are more important during a summer drought" (Waring and Franklin, 1979).

The forests of the Pacific Northwest grow under a wide range of temperature and moisture regimes. In western Oregon and Washington, the mean annual temperature range is about 5°C, while in the forested regions of Idaho the seasonal variation in temperature is greater. Annual precipitation varies from 40 - 60 cm on the east slope of the Cascades to about 300 cm in the coast ranges of Oregon and Washington (WIC 1974, Gholz 1982, Franklin et al., 1991). In Idaho forests annual precipitation ranges from about 60 - 150 cm (WIC 1974). Depending on the temperature and elevation, winter precipitation falls as either rain or snow; significant snow pack occurs at higher elevations. Orographic and elevational influences on precipitation are stronger than the latitudinal influence. Rain shadow effects are particularly evident east of the crest of the Olympic Mountains and Cascade Mountains (Dolph et al. in press).

Transects of weather stations (NOAA 1989a,b) along the coast and in the mountainous regions from southern Oregon to northern Washington illustrate the temperature and precipitation gradients in the western hemlock and Sitka spruce forest zones (Tables 3 and 4, Figs. 2-4). The north to south temperature gradient is steeper in the winter than the summer. Similarly, there is a large northward decrease in the duration of the growing season from 365 days at Gold Beach, OR to

281 days at Forks, WA. The growing season becomes shorter and the temperatures lower as the elevation increases. Mean July temperatures only reach 11.4° and 12.8°C at Rainier/Paradise (1654 m), WA and Crater Lake (1975 m), OR, respectively, with five to six months having mean monthly temperatures below 0°C.

## Adaptation of Forests to Current Climate

The distinctive seasonality of precipitation in the Northwest is a strong determinant of regional vegetation patterns. Evergreen conifers are well-adapted to this climatic regime in contrast to hardwood species. These adaptations, summarized by Waring and Franklin (1979), include 1) the ability to photosynthesize under cool winter temperatures, 2) needle-shaped leaves which reduce leaf temperature and respiration during the warm dry summer, 3) a large volume of sapwood that stores water which can be utilized during dry summer days, and 4) the ability to reestablish their vascular water column if it is broken during evaporative stress, whereas many hardwood species can not (Sucoff 1969, Burke et al. 1976, Sakai 1983).

Within the region, lower elevational ecotones are controlled primarily by soil moisture, whereas upper elevational ecotones are controlled either by temperature or by competition with higher elevational species (Daubenmire 1943, Zobel et al. 1976, Franklin 1988). Snowpack and wind can be important controls at higher elevations in the Cascades and Olympic Mountains (Scott 1980). Leverenz and Lev (1987) point out the seed chilling requirement for successful regeneration of Douglas-fir in coastal regions. Seedling establishment is limited the following spring and summer if a winter month does not have a mean temperature below 9.3°C (Copes 1983).

## Sensitivity to Future Climate Change

Climate change of a sufficient magnitude will affect regional vegetation patterns. A key question is: how much can the climate change before significant vegetation redistribution takes place? One way to answer this is to analyze the response of vegetation to past climate variation. Forest growth tends to be higher in years with warmer than normal winters, and cooler summers (Peterson and Heath 1990). Within the historical record, short-term droughts had little impact on vegetation (Graumlich 1987). Over the past few centuries, droughts similar to those of the 1920s and 1930s occurred at least once every century since 1675, as determined by tree ring analysis (Graumlich 1987). This variation in climate obviously affected tree growth, but did not change regional vegetation patterns.

In the longer term, temperatures were about 2°C warmer during the early Holocene (10,000 - 7,000 years before present), during which time the vegetation was much different from today's (Brubaker 1988). Douglas-fir was more important than today in western Washington, and oak savanna extended north of its present limit in Oregon's Willamette Valley to the southern part of the Puget Trough (Barnosky et al. 1987). Thus, it appears that a warming of at least 2°C will have significant impact on regional vegetation patterns.

A complicating factor in assessing forest sensitivity to climate change is the long life spans of trees in the Northwest (500 - 1000+ years; Brubaker 1986, Franklin 1988, Franklin et al., 1991). Adverse climate conditions may eliminate seedling establishment and sexual reproduction while mature trees may be able to survive for several centuries. Under these conditions, the current vegetation can be considered to be "out of equilibrium" with the new climatic regime, since the climatically favored vegetation succession from bare ground would lead to a vegetation type different than what currently persists in the area.

A disturbance such as fire would speed the conversion to the new vegetation type favored by the new climatic conditions. Otherwise, vegetation change would be much slower and depend on the senescence of mature trees. The ability of the major Northwest tree species to reproduce asexually (e.g., by sprouting from root stocks) is limited, and thus asexual reproduction would not be an important mechanism influencing the response of forests to climate change in the region. An important point is that adverse climate conditions as defined in this context likely have upper as well as lower limits. Mature trees can be killed by severe climate conditions as well as seedlings, but simply may have higher tolerance limits. Thus, if a climate change is large enough, mature trees could die, eliminating their potential role in slowing vegetation change in response to climate change. Establishing the climatic tolerances of mature trees will be important for future assessments of climate change impacts on Northwest forests.

## METHODOLOGY

The sensitivity of Northwest forests to climate change has been analyzed using a variety of modeling techniques as well as expert judgement based on an understanding of how climate controls the current distribution of forest types in the region. The modeling analyses are complementary, as no single vegetation model can currently provide the specific detail and geographic context needed in an impacts assessment. The limitations and assumptions of the specific modeling analyses will be described in the results section.

### Generation of Climate Scenarios

Four general circulation models (GCMs), Oregon State University (OSU; Schlesinger and Zhao 1989); Goddard Institute for Space Studies (GISS; Hansen et al. 1983); Geophysical Fluid Dynamics Laboratory (GFDL; Manabe and Wetherald 1987); and United Kingdom Meteorological Office (UKMO; Wilson and Mitchell 1987) were used to project future climate conditions assuming a doubling of current $CO_2$ concentrations. Because the grid box sizes of each model (typically about 4° latitude by 5° longitude) are large relative to the area of the Pacific Northwest, the models cannot be expected to reproduce the spatial hetereogeneity of current or projected future climate. They can, however, provide insight into climatic change over broad regions caused by increases in atmospheric $CO_2$ concentration (Jenne 1988). To create a climate change scenario, the ratios of $2xCO_2$ and $1xCO_2$ GCM model run variables were used to multiply current mean monthly temperature and precipitation for the locations of interest (Parry et al. 1987, Smith and Tirpak 1989). Temperatures were first converted to °K before calculating the ratios.

### Vegetation Modeling - Application of the Holdridge Life-Zone Classification

The Holdridge Life-Zone classification system (Holdridge 1947, 1967) has been used to simulate the effect of climate change on global vegetation patterns (Emanuel et al. 1985a,b; Prentice and Fung 1990, Leemans 1990, Smith et al., 1991). We will summarize the results of Leemans (1990) and Smith et al. (1991) for the Pacific Northwest. Although they applied the classification system at a relatively coarse resolution (0.5° x 0.5°) considering the size of the region, the Holdridge results are the only published data currently available that provide estimates of regional changes in the distribution of forests throughout the Northwest.

The Holdridge Life-Zone classification system relates major vegetation formations to mean annual biotemperature, precipitation, and the ratio of potential evapotranspiration (PET) to mean annual temperature. Biotemperature is basically an index of the growing season. PET as defined by Holdridge (1967) is a linear function of biotemperature, and thus is not an independent variable in this model. Using these climate variables, Holdridge created a triangular axis system relating climate and vegetation (Fig. 5). Leemans (1990) and Smith et al. (1991) applied the Holdridge classification system to a gridded (0.5° x 0.5°) global database of mean monthly temperature and mean annual precipitation (Leemans and Cramer 1990) for current climate, and created future climate scenarios using the GCM data described above.

### Vegetation Modeling - Local Climate-Forest Zone Correlations

Franklin et al. (1991) used correlations of climate and forest zonation in the central Oregon Cascades to estimate changes in the areal extent of forest communities in response to either a 2.5° or 5°C warming scenario. These warming scenarios are similar to the OSU and GFDL simulations for the region (Table 2). The current relationship between temperature and forest zones was used to define the new elevational bands the forest zones would occupy under these two scenarios. Then the areal extent of the forest zones at their new elevations was determined using an elevation model relating area with a given elevational band. These results are more detailed than the Holdridge simulations, but are limited to the central Oregon Cascades.

### Vegetation Modeling - Forest Gap Models

Models that simulate forest dynamics on small plots (usually 1000 $m^2$) have been developed for a variety of forest communities worldwide (Shugart and West 1980). The models were initially devised in order to simulate forest succession in a gap formed in a closed forest produced by the death of an overstory tree. In recent years, these models have been used to estimate changes in species composition in response to climate change (Solomon 1986, Botkin et al. 1989, Dale and Gardner 1987, Urban and Shugart 1989, Bonan et al. 1990). The models simulate tree growth for every individual tree on a plot, as well as seedling establishment and tree mortality. Mathematical functions of key demographic processes (e.g., annual diameter growth) are derived for the maximum potential growth of each tree species included in the model. Growth rates are then reduced according to environmental constraints such as shading, soil moisture, and temperature (Urban and Shugart 1989). Thus, environmental feedbacks are an important component of these models. As a forest gap closes, available light decreases at the forest floor, shifting the probability of sapling establishment from shade intolerant species to shade tolerant species. Since the models incorporate stochastic processes, a large number of plot simulations are run and the average results presented as the model output.

Forest gap models were initially developed for eastern deciduous forests (Botkin et al. 1972, Shugart and West 1977), but several gap models have been developed for western forests (Dale and Hemstrom 1984, Kercher and Axelrod 1984, Urban et al. 1990). Two models have been used to simulate climate change effects in the Pacific Northwest, CLIMACS (Dale and Hemstrom 1984, Dale and Franklin 1989) and ZELIG (Urban 1990, Urban et al. 1990).

CLIMACS was modified from FORET (Shugart and West 1977) for application in western Washington and Oregon. The major modifications include introducing a moisture factor in the growth equations, calculating regressions of height to diameter for use in the annual growth equations, and making mortality dependent on successional class of the species (Dale and Hemstrom 1984, Dale et al. 1986). The model was run assuming a 5°C warming in northwest Oregon, using data from Cascade Head on the Oregon coast. Soil moisture status was not changed in the scenario. The climate change scenario was applied to a typical stand structure of a forest 140 years old at Cascade Head on the Oregon Coast.

ZELIG is an updated version of the FORET model as well (Urban 1990) and was used to simulate climate change impacts at three sites in Washington and Oregon (Urban et al. 1990). The major effort in implementing the model in the Northwest was developing a set of species parameters (e.g. growing degree day limit which is a measure of the cumulative increase in temperature over the growing season) describing life history and growth characteristics for each Northwest tree species. In contrast to the eastern United States where the topographic relief is substantially less, tree species in the mountains of the Northwest often have local upper and lower elevational range limits within their overall geographic distributions. Correlations of climatic variables and these range limits were thus established at a number of latitudinal bands from northern California into British Columbia.

ZELIG.PNW.1 was initially tested at the H.J. Andrews Experimental Forest and LTER site (44.2°N, 122.2°W) in the central Oregon Cascades because of the large amount of forest stand data available for model verification (Fig. 2). The model was used to simulate forest composition for the full range of current climatic conditions at the forest. The climate parameters defining the range limits of species at the H.J. Andrews' latitude (44°N) were used in the model run. Model simulations started from bare ground (in contrast to the CLIMACS simulations) and ran for 500 years. ZELIG was used to simulate the response of a forest at 500 m to the OSU and GISS climate change scenarios.

The sensitivity of forest dynamics at Mount Rainier, WA, and Gold Beach, OR, to climate change was also simulated (Fig. 2) using the mean climate data from those sites but with the climate variability data from H.J. Andrews. The species parameter sets for 44°N was used in these simulations rather than the locally defined sets. Thus, these results must be viewed as more tenuous than the results for H.J. Andrews because of the potential differences in the climatic tolerances of tree species at these two different sites.

ZELIG was also used to investigate the transient response of Northwest forests to climate change. Transient climate changes were applied to the model as linear increases in growing degree days (GDD) starting at a specific year and increasing to a prescribed limit after a specified number of years. The increase was started at year 0, 200, and 500 in separate simulations, and either a 600 GDD or 1300 GDD warming was applied. A 600 GDD warming corresponds to the OSU 2x$CO_2$ equilibrium scenario, and the 1300 GDD increase corresponds to the GISS 2x$CO_2$ equilibrium scenario (Urban et al. 1991).

## Carbon Model Results

Potential changes in carbon storage in the central Oregon Cascades were analyzed using the DFC model (Harmon et al. 1990). This model tracks carbon stored onsite (e.g., changes in ecosystem storage) and offsite (e.g., the fate of harvested wood). A 5°C warming scenario was applied at three elevations in the Oregon Cascades (Urban et al. 1990).

# RESULTS

## Potential Climate Changes in the Pacific Northwest

The GCMs project a significant warming of the climate in the Pacific Northwest under double $CO_2$ conditions. As an example of the magnitude of regional changes in climate, annual mean temperatures in the Willamette Valley are projected to increase from 2.3° to 6.7°C (Table 2). The UKMO predicts the greatest warming, with January temperatures increasing 5-6°C, and July temperatures increasing 9-11°C. The temperature seasonality is projected to persist under climate warming with all months showing an increase (Fig. 3). Growing degree days are projected to increase significantly (Table 3). In western Oregon and Washington the OSU GCM projects a 27 to 72% increase in growing degree days while the GISS model projects significantly more warming (76 to 171%). Percentage increases in growing degree days are greatest at higher elevations.

There are no seasonal shifts in precipitation projected by the GCMs; the pattern of relatively dry summers and wet winters will persist (Fig. 4). However, the proportions of rain and snow may change from current conditions because of the increase in temperatures. Two of the GCMS (OSU and GFDL) predict unchanged (2 to 4% increase) annual precipitation, while the other two (GISS and UKMO) predict about 20% greater annual precipitation (Table 2). Overall, the UKMO scenarios presents the largest change from current conditions, particularly the large increases in summer temperature.

In terms of the impact on vegetation, changes in soil moisture are of greater interest than changes in precipitation alone. Changes in soil moisture depend in a large part on potential evapotranspiration (PET), estimates of which are listed in Table 4. PET values are dependent on the method of calculation and must be viewed as preliminary estimates at this time (Marks 1990). Dolph et al. (in press) have developed a regional water balance model for the Columbia River Basin. Application of their model with the GFDL climate scenario suggests that soil moisture could decrease by over 50% in the region.

The climates projected from the GCMs represent a significant shift from present conditions. When viewed in a south to north transect, the projected temperature changes are equivalent to shifting current climates 200 to 500 km north, i.e., moving the climate of northern California into northern Oregon (Franklin et al., 1991). However, strict geographic analogues of future climate are difficult to define since precipitation is projected to remain unchanged. Thus, it is more precise to say that the temperature regime of northern California will be imposed on the precipitation regime of northern Oregon. Similarly, from an elevational perspective, the climate projections suggest a 500 to 1000m upward movement of temperature regimes (Franklin et al., 1991).

## Holdridge Vegetation Scenarios

### Simulation of Current Vegetation

Before presenting the climate change results it is important to consider how well the vegetation model simulates today's vegetation patterns. The Holdridge classification presents a much coarser taxonomic resolution of vegetation in the Northwest (Table 5, Figures 6-9) than summarized in Figure 1 and Franklin and Dyrness (1988). However, the Holdridge system does a good job of separating forest from non-forested land. The Holdridge estimate of forested land in the region (318,000 $km^2$) reasonably approximates the Forest Service estimate (290,000 $km^2$; USDA 1990). The main forest types simulated under current conditions are temperate forest and boreal forest, whereas the SAF classification has eight major forest types delineated (Fig. 1; USDA 1970). All the forests west of the Cascade crest are considered to be temperate forests, while subalpine forests are predicted for parts of the Cascade crest, and portions of the Northern Rocky Mountains in Idaho. The Holdridge model does not depict the heterogeneity of forest vegetation in central Idaho.

## Estimated Vegetation Change

Major shifts in vegetation patterns occur in the Northwest under four climate change scenarios, using to the Holdridge system (Smith et al., 1991). Overall, 26% (OSU) to 90% (UKMO) of the tri-state region will change from one Holdridge vegetation class to another (Table 5, Figs. 6-9). Total forested area decreases under all scenarios from 5% (OSU scenario) to 25% (GFDL scenario). Specifically, boreal (subalpine) forests will decrease by at least 50%, (OSU scenario) or be eliminated (UKMO scenario). Similarly, three climate change scenarios project declines (8 to 50%) in the area of temperate forests; in contrast, the OSU scenario projects a 20% increase in temperate forest area. In contrast to the decline in temperate forests, all four climate scenarios project that warm temperate forests expand manyfold.

Interpreting these changes in vegetation in terms of the distribution of the forest types defined earlier is somewhat problematic. If one compares the current distribution of forest types and the Holdridge classes, temperate forests in the Northwest correspond to the entire suite of conifer forests in the region. Warm temperate forests are only found in the southeastern United States, corresponding to oak dominated forests as mapped by Kuchler (1964). Thus it appears that under double $CO_2$ conditions, the western hemlock - Douglas-fir forests decrease in regional extent, being replaced by more drought tolerant conifer (e.g., the dry Douglas-fir series or ponderosa pine) and oak vegetation types.

## Assumptions/Limitations

Application of the Holdridge Life-Zone classification system to simulate future vegetation patterns involves several significant assumptions and has several limitations. First, the Holdridge system is assumed to adequately define current vegetation patterns in the region, and second, that current climate-vegetation correlations are unchanged in the future. Although the Holdridge system correctly classifies only 40% of the globe's vegetation (Prentice 1990), the model does better in correctly classifying forest and nonforest vegetation in the Northwest. However, it is uncertain whether current climate-vegetation correlations will remain unchanged in the future. New broad-scale vegetation models are being developed (Neilson and King in press; I.C. Prentice, personal communication, Uppsala University) which are based on a mechanistic understanding of how climate controls vegetation patterns. These models should be more robust when driven by climatic conditions different from those of today.

The Holdridge classification system cannot be used to simulate the dynamics of vegetation change (e.g., tree establishment, migration, or succession). The climate change results must be viewed as a snapshot of future vegetation patterns after the vegetation has responded to a double $CO_2$ climate change. Lags of unmanaged vegetation response to climate change could be significant over a decades to century time scale (Davis 1989).

The Holdridge model simulates only potential natural vegetation; current land use is not considered. The influence of soils on vegetation is not factored into the analysis, nor are the direct effects of higher $CO_2$ concentrations on plant growth. Finally, the life zone classifications are very broad and applied on a coarse resolution. Consequently, the broad classification system could mask some vegetation change. For instance, a climate change could produce changes in species composition within a gridbox but not be significant enough to change the overall Holdridge classification of the vegetation in the gridbox.

### Local Climate-Forest Zone Correlations

Mean annual temperatures of adjacent vegetation zones in the region differ by about 1.5° to 2.0°C at Mount Rainier, WA (Franklin 1988) and 2.5°C in southwestern Oregon (Atzet and Wheeler 1984, Franklin et al., 1991). Thus, a 2°C warming would completely shift a forest type one zone upward; a 4°C warming would shift it two zones upward (Franklin et al., 1991).

More specifically, on the west slope of the Cascades, the dry Douglas-fir series would increase from 8% of current forested land to 39% (2.5°C warming) or 27% (5.0°C warming) (Figs. 10 and 11) using current climate/forest correlations (Franklin et al. 1991). The moister western hemlock - Douglas-fir forests would decrease in areal extent, as would subalpine and alpine forests. The reduced area of upper elevational forests is simply a function of the decrease in area occupying each successive elevational band up a mountain. Subalpine and alpine vegetation could be eliminated locally if their new elevation limits are above local mountain crests.

On the east slope, sagebrush steppe increases substantially in areal extent, while juniper and ponderosa pine forests decrease in areal extent (Fig. 11). Total forested area would decrease east and west of the Cascade crest, particularly under the +5.0°C scenario.

Assumptions/Limitations

This correlational approach has the same limitations as those discussed for the Holdridge approach, except that the taxonomic resolution is much finer. Also, the approach assumes that current forest zones will not significantly change in composition. However, paleoecological data clearly indicate that this assumption is incorrect. Species moved independently in the past in response to warming after deglaciation and at times formed assemblages without modern analogues (Davis 1981, Webb 1986). Each species has its own unique set of climate limits. Thus vegetation change in the future will certainly be more complex than suggested here.

Forest Gap Models - CLIMACS Results

Simulation of Current Forests

The ability of the CLIMACS model to simulate forest dynamics under current climatic conditions has been verified against data from H.J. Andrews (Hemstrom and Adams 1982) and validated for the western Olympic Peninsula. For xeric and mesic sites at Andrews the model correctly predicted Douglas-fir as the dominant tree and modeled and measured leaf area and basal area compare favorably. For the Olympic Peninsula site, the model correctly projects Douglas-fir as dominant with western hemlock and silver fir in the understory (after 500 years). The size distribution of trees is similar for both modeled and measured stands (Dale et al. 1986).

Estimated Changes in Forest Compositions

CLIMACS was run under a 5°C warming scenario for Cascade Head, OR (Dale and Franklin 1989). Under current climate conditions, the composition of the stand would change from one dominated by Douglas-fir to one dominated by western hemlock, the typical forest succession pattern in the region (Fig. 12). Silver fir would be a co-dominant. Under the warming scenario, western hemlock also succeeds Douglas-fir as the dominant tree. However, grand fir replaces silver fir as a co-dominant (Fig. 12).

Assumptions/Limitations

The limitations of gap models will be discussed fully after the ZELIG results are summarized. One limitation, unique to the CLIMACS analysis, is that soil moisture was not altered, so the drought effects of warming were not analyzed. Drought effects could be quite pronounced in the Northwest under the GFDL and UKMO scenarios.

Forest Gap Models - ZELIG Results

Simulations of Current Vegetation

The results of the correlations of tree species range limits with climatic parameters at a number of latitudinal bands in the Northwest indicate that these correlations can vary with latitude. In fact, for some species the maximum growing degree day (GDD) limit at higher latitudes is less than the minimum limit at lower latitudes. There are several explanations for this, ranging from genetic variation within a species to the possibility that some other environmental factor (soil moisture, snow pack, wind) besides GDD limits species distributions in some parts of their range (Urban et al. 1990).

The latitudinal variation of the species-climate relationships complicates the forest gap modeling because a decision needs to be made as to what species parameters should be input into the model when the model is run at a particular site. The choices range from either the parameter suite at or near the latitude of the simulation site, or the overall regional limits. In this analysis, parameters for the latitude of the H.J. Andrews site were used in the model runs.

The results from the ZELIG simulations for current and future conditions at Gold Beach, OR; H.J. Andrews Forest, OR; and Mount Rainier, WA, are summarized in Figure 13. The model does a poor job of simulating current vegetation patterns at H.J. Andrews. At an elevation of 500 m, Douglas-fir and western hemlock are the dominant trees in the current forests. However, in the model simulation, chinkapin and ponderosa pine are dominant, and Douglas-fir and western hemlock are only minor components of the modeled stand. In essence, the model predicts vegetation adapted to much drier sites than occur at H.J. Andrews. The model performs better at 1000m, where Douglas-fir and western hemlock dominate both natural and modeled stands (Urban et al. 1990). Douglas-fir is still underestimated by the model, however.

A priori one would expect the model not to perform as well at the Gold Beach and Rainier sites because of the apparent latitudinal differences in species adaptations to climate. At Gold Beach, where annual precipitation is greater than at the H.J. Andrews and annual temperatures are 1.8°C warmer, current forests are dominated by western hemlock and Sitka spruce (Franklin and Dyrness 1988). ZELIG predicts chinkapin and tan oak as forest dominants. Sitka spruce is absent from the simulated stand, and western hemlock is a very minor forest component. Again the model is biased towards predicting a drier type of vegetation than what actually occurs at the site.

ZELIG does a better job of simulating forests at Mount Rainier. Current forests at 1600m are dominated by mountain hemlock and silver fir, with subalpine fir present (Franklin and Dyrness 1988, Franklin et al. 1988). ZELIG predicts that silver fir, mountain hemlock, western white pine, and subalpine fir would be common forest species, which is a reasonable approximation of current conditions.

In sum, ZELIG appears to do reasonably well in cool sites, but becomes increasingly biased towards too xeric a forest in warmer sites. That is, as the site temperature increases, the model error increases.

## Estimated Changes in Forest Composition

ZELIG predicts major changes in species composition under the OSU and GISS climate scenarios (Fig. 13). Under the OSU scenario at H.J. Andrews, the dominant trees simulated under current conditions are replaced by tanoak and red alder. At Gold Beach, dominants simulated under current conditions are replaced by red alder. The simulated vegetation response to climate change is less at Mount Rainier. The largest change is the replacement of mountain hemlock by western hemlock.

The driving factor behind the forest changes is the increase in GDD at each site. Even under the moderate warming of the OSU scenario, only a few species have maximum GDD limits less than the GDD calculated for the new climate conditions. For instance, at Gold Beach, only red alder and tanoak will grow given the GDD value for the OSU scenario.

The increase in temperature under the GISS scenario is so great that projected GDD at H.J. Andrews and Gold Beach exceed the maximum values for any species included in the Northwest modeling effort. Thus, the model simulates no tree growth at these sites.

At Rainier, silver fir becomes a minor component with western hemlock and Douglas-fir becoming more important. Basically ZELIG predicts an upward movement of species distribution in the Washington Cascades.

Recall that the OSU and GISS scenarios are the least severe of the four scenarios presented in Table 2. The amount of warming in the GFDL and UKMO scenarios is probably sufficient for GDD limits to exceed those of any tree species in the ZELIG parameter set. Consequently, ZELIG would predict an absence of tree growth under these two scenarios.

The general response of Douglas-fir forests at 1000m in the H.J. Andrews Forest to the transient climate scenario varies with the stand age of the forest when the warming was applied (Urban et al. 1991). If the warming is applied at a stand age of 200 or 500 years, a short episode of high tree mortality occurs and the woody biomass on the plot decreases by 50% (OSU equivalent warming) or 90% (GISS equivalent warming). The total stand biomass does not return to prewarming levels because of the model imposed growing degree constraints on tree growth, as discussed above. If the warming begins at the beginning of the forest simulation, succession to more heat tolerant species proceeds without significant forest dieback. At higher elevations, an OSU equivalent warming imposed on a 200 year-old stand causes a gradual shift in species composition and biomass returns to pre-warming levels. A GISS equivalent warming produces a mortality episode as at lower elevations, and woody biomass is reduced by about 25%. These results are distinctly different from the CLIMACS results, in which total biomass did not drop after a climate change was imposed on a young stand.

### Assumptions/Limitations

A number of assumptions are made when the two forest gap models are applied in the Northwest. In developing correlations between climate and species distribution, it is assumed that current species distribution reflects the species' environmental tolerances, and that species grow best at the center of their range (Urban et al. 1991). Temperature (through growing degree day totals) is assumed to be the primary control of species range limits. Genetic variability within a species parameter set is assumed to be nonexistent. Seeds of all the species included in the simulation are assumed to be instantaneously available if the climate is favorable for their germination. The form of the species-response functions to climate is assumed to be correct and similar for all species. Other model assumptions are discussed by Urban et al. (1991).

The limitations of Northwest forest stand models are substantial at this point in their development. Of particular concern is the inability of the ZELIG model to adequately simulate low elevation (warm) forests in the Northwest. A potential reason for the poor simulation of low elevation forests is that ZELIG does not adequately account for the importance of soil moisture in controlling species distributions at lower elevations (Daubenmire 1968, Zobel et al. 1976, Waring and Franklin 1979, Neilson et al. 1989). Furthermore, both gap models do not modulate soil moisture or transpiration by vegetation density.

Another limitation of the gap models is the expression of some species specific parameters on a relative basis. These parameters could change as assemblages change in response to a changing climate. In the current simulations they remain constant as climate changes. Finally, the gap models, similar to the other simulation approaches summarized in this paper, do not consider the direct effects of enhanced $CO_2$ concentrations on water use efficiency or changes in disturbance frequencies (Urban et al. 1991).

Because of the model limitations, the $2xCO_2$ scenarios presented here should be interpreted in terms of the relative change in species composition rather than specific predictions of changes in individual species dominance. In particular, since ZELIG has difficulty simulating current forests under relatively warm and dry conditions, its simulations of forest composition under warmer future climate conditions are likely to be biased.

### Potential Changes in Carbon Storage

A climate warming of 5°C could decrease detrital carbon stores by 30% across a diverse array of sites through the increase in respiration rates (Urban et al. 1990). At low, middle, and high elevations in the Oregon Cascades this could result in fluxes of 40, 55, and 75 Mg C per hectare to the atmosphere, respectively. Production would have to increase by about 10% to offset these losses. The increase in production is unlikely except at middle elevations. Production at low elevations could be constrained by low soil moisture and replacement of Douglas-fir by slower growing species. Shallower soils at higher elevation or absence of appropriate mycorrhizal fungi and soil bacteria for upward migrating tree species may limit production increases there (Perry et al. 1990). Thus, assuming no change in production, and weighting the detrital carbon loss by the areal extent of each elevation zone as done by Franklin et al. (1991), there could be a net loss of 60 Mg carbon per hectare from the Oregon Cascades.

This analysis does not consider changes in species composition, or the potential for catastrophic forest dieback to inject a pulse of carbon into the atmosphere (Neilson and King in press). Predicted changes to less-productive forests adapted to warmer and drier conditions could substantially reduce the amount of carbon stored in the Northwest over an extended period of time.

To put the potential carbon loss in perspective, conversion of old growth forests to younger plantations in western Oregon and Washington is resulting in declines in carbon storage of 305 - 370 Mg per hectare (Harmon et al. 1990).

### Expert Judgement - Effects of Climate Change on Forest Disturbances

Although not quantitatively modeled in the Northwest, as of yet, the effects of climate change on forest composition and structure could be felt initially and most extensively through altered disturbance regimes (Cwynar 1987, Neilson et al. 1989, Graham et al. 1990, Overpeck et al. 1990, Franklin et al. 1991). Disturbances reduce the resilience of existing forests and can be viewed as events that hasten the adjustment of forest vegetation to new climate conditions. As noted by Brubaker (1986), disturbances decrease the time lags in vegetation response imposed by "long tree lifespans by accelerating rates of population decline when climate change makes conditions unfavorable for seedling establishment." As an example, the postglacial increase in Douglas-fir and decline in western hemlock populations was caused by a climatically induced change in fire frequency (Cwynar 1987).

However, disturbances could also create more severe conditions for forest reestablishment under changing climates (Franklin et al. 1991). Transitions in vegetation types could be a problem as forest loss through fires may occur faster than forest reestablishment, especially at the lower and upper tree lines. Changes in soil conditions caused by a loss of forest cover could slow forest reestablishment (e.g., Perry et al. 1990; discussed in more detail in the transient dynamics section). Consequently, there could be a shift in area from forest to nonforest vegetation (Franklin et al. 1991).

Fire frequencies are likely to increase in the region given increased temperatures, small changes in precipitation and higher potential evapotranspiration and consequently drier fuels (e.g., Clark 1988). The key factor in determining fire frequencies will be the number of ignition events, which currently may limit fire frequency in the region. How these will change in the future is unknown, although warmer summer temperatures may increase convective storms and thus lightning (Overpeck et al. 1990). Drier fuels may increase the spread potential of fires, which could also effectively increase fire frequencies. Buildup of fuels over the past 100 years due to fire suppression efforts may increase the severity of fires (Kaufmann 1990). The potential effectiveness of fire control methods to control future fires is uncertain. The 1988 Yellowstone National Park fires clearly illustrate the ability of a fire to burn uncontrolled through a region even when a large fire control effort is mounted.

New or more severe insect problems are probable given projected climate change. The altered climate may provide a more favorable environment for insects or trees may become more susceptible to insect pests as a consequence of climate-change increases in tree stress (Mattson and Haack 1987, Graham et al. 1990). For example, the balsam woolly aphid (*Adelges piceae*), is an introduced pest that can be a serious problem in the Pacific Northwest in Pacific silver fir and low-elevation occurrences of subalpine fir (Mitchell 1966, Franklin and Mitchell 1967, Franklin et al. 1991). Currently, the aphid has been restricted to low and middle elevations by temperature limitations. During the summer the second generation of the aphid must reach the first instar stage to survive the winter. The higher subalpine zones of the costal and Cascade mountains rarely experience sufficient heat for the second generation to develop sufficiently to overwinter, hence too few aphids attain the critical stage to produce dense populations (Mitchell 1966, Franklin et al. 1991). However, given the large increase in growing degree/days (Table 3) and mean temperature increases of 2° to 5°C, it would be possible for the aphid to successfully reproduce and spread at the higher elevations where subalpine fir is a major component (Franklin et al. 1991). Mature subalpine fir are susceptible to the aphid; consequently high levels of subalpine fir mortality are likely (Franklin et al. 1991). Increased pest damage could increase forest fuels and thus fire frequencies.

The human imposed disturbance regime of timber harvesting could also speed the response of forest vegetation to climate change. A shift to shorter rotation times, preferential cutting of declining forests, and subsequent planting of seedlings better adapted to the new climate would speed the response of regional forests to climate change. In some respects then, intensively managed forested landscapes may have the potential to be less sensitive to climate change than unmanaged forested ecosystems (Davis 1989).

However, current forest management may complicate the response of forests to climate change. The elimination of shrubs from plantations may eliminate mycorrhizae required by conifers for growth and thus reduce forest growth after fire (Amaranthus and Perry 1987, Franklin et al. 1991). Elimination of shrub and hardwood nitrogen fixers may reduce soil fertility in the long run and affect the potential response of forests to climate change (Perry and Maghembe 1989). Also, young forest plantations may be more susceptible to fire than older forests (Perry 1988). Maintenance of forest biodiversity with climate change may be more difficult in a heavily managed landscape because of the fragmentation of ecosystems.

In sum, natural and human caused disturbances of the landscape will play a major role in the response of regional forests to climate change. The interplay of forest management and natural forest processes needs to be considered in future assessments of climate change impacts on Northwest forests. They also must be considered in designing mitigation options for reducing the impact of climate change on regional forests.

## Major Uncertainties in Projecting Forest Response to Climate Change

### Transient Dynamics

The model results presented here assume an abrupt climate change to double $CO_2$ conditions and simulate the equilibrium response of vegetation to that climate change. That is, the models simulate vegetation patterns in the region after species have responded to the climate change. One reason for this simple approach is the difficulty in simulating transient climate change (IPCC 1990). But ecosystem models also are limited in their ability to simulate transient dynamics. Broad-scale vegetation models that simulate the equilibrium response of vegetation to climate change are still being refined; development of regional-scale models to depict transient behavior of vegetation is a more ambitious goal requiring much more research. Local-scale models, such as forest gap models, can simulate transient dynamics provided a climate scenario is provided. Several scenarios of the transient response of forests to climate change have been produced for other parts of the United States (Urban et al. 1989, Botkin et al. 1989).

A key problem in the simulation of vegetation dynamics is incorporating plant migration and disturbance into the modeling framework. The importance of disturbance in affecting vegetation change has been discussed, and approaches are being developed to model fire regimes on forested landscapes (e.g., Keane et al. 1989). The movement of species across the landscape will need to be simulated in order to determine whether a climatically favored species will actually be present in an area and thus available for growth. Current and future land use will affect species migration and should be considered in vegetation modeling efforts (Graham et al. 1990).

The influence of species migration rate on vegetation response to climate change may be less important in the mountainous regions of the Pacific Northwest than in the eastern U.S. (e.g., Franklin et al. 1991). In the relatively flat terrain of the eastern U.S., a 1°C temperature change will move a climate zone a considerable distance latitudinally. However, in mountainous regions of the West, a 1°C change will shift a climate zone up only a few hundred meters of elevation and perhaps only a few kilometers in actual distance. Thus, western tree species will have shorter distances to migrate to track their favored environment (as long as the temperature change does not raise the preferred climate zone above the highest elevation in the local region). Planting of species beyond their normal dispersal distances as part of climate mitigation efforts will likely eliminate this west-east distinction for many managed ecosystems (Davis 1989).

Realistic modeling of the transient vegetation response to climate change will also need to include land use, soil effects on vegetation, and climate variability. Briefly, land use can affect migration rates by imposing barriers to dispersal, whereas active forest management to mitigate climate change impacts may speed the response of forests. Migration of tree and other plant species may be limited by soil fertility and biology (Perry et al. 1990). Finally, changes in future climate variability and the nature and frequency of extreme events could have dramatic effects on vegetation. Increased drought frequencies could increase fire frequencies and favor drought/fire adapted species. Unfortunately, predicting changes in climate variability under double $CO_2$ conditions is difficult. All of these factors make the dynamic simulation of vegetation response to climate change a very complex task.

Despite the difficulty in simulating transient vegetation change, it is critical that transient effects be at least qualitatively considered in climate change impact assessments. The principle reason for this is that climate and ecosystem feedbacks that occur during a transient change could alter the trajectory of the vegetation response to climate change, and lead to a different steady-state than that predicted from a strictly equilibrium model. For example on the landscape scale, consider a fire at a higher elevation site in the Cascades after climate has changed sufficiently to prevent reproduction of the established trees. Even short migration lags of lower elevation species to the exposed site could result in further changes in site conditions. Soil fertility could be reduced by changes in soil structure and loss of microorganisms and nutrients caused by the loss of forest cover (e.g. Perry et al. 1990). These changes could prevent the establishment of the climatically favored tree species and result in the establishment of a grassland, even though steady-state model would predict a forest should occupy the site. On the global scale, rapid climate change could cause widespread forest dieback and forest fires, releasing up to 3 Gt of carbon to the atmosphere per year (Neilson and King in press). In comparison, current fossil fuel releases are 6 Gt/yr (Marland et al 1989). The additional radiative forcing could cause more warming than that predicted assuming no transient change in terrestrial carbon storage (Neilson and King in press). The additional climate change could further change vegetation patterns. Thus, vegetation response could be larger in the transient simulation than in an equilibrium simulation.

## Direct Effects of $CO_2$

The potential effect of higher $CO_2$ concentrations on forested ecosystems is highly uncertain. Many assessments of the impacts of climate change on forests have focused on the direct effects of increased temperature and drought on the trees, but have not quantified the potential impacts of elevated $CO_2$ on forests.

There is a substantial body of literature showing that photosynthesis is increased and stomatal conductance decreased by supra ambient levels of $CO_2$ (Surano et al. 1986, Hollinger 1987, Ågren et al. 1991). However, the magnitude of the resulting changes, especially for mature trees, is uncertain. Also, it is largely unknown if the changes in photosynthesis and conductance will persist as the trees acclimatize to the elevated $CO_2$ or if the increases can be supported by current water levels in the forest soils.

The extent to which possible nutrient limitations in forest soils will limit the direct effects of $CO_2$ on productivity is also unknown. In a review of a series of experiments on the response of seedlings and young trees to $CO_2$, Jarvis (1989) concluded that tree growth was stimulated by added $CO_2$ even under severe nutrient limitations. However, it is not known if these stimulations will persist in mature trees in nutrient-poor soils.

Studies with loblolly pine (*Pinus taeda* L.) seedlings found that drought stress did not preclude a growth response to elevated $CO_2$, and that the effects of drought stress were largely mitigated by elevated $CO_2$ (Tschaplinski and Norby, 1991). The reported decreases in stomatal conductance and increases in photosynthesis yield an increase in water-use efficiency by trees (Conroy et al., 1988).

A key issue in the $CO_2$ debate is how will vegetation over a landscape respond to higher $CO_2$ concentrations. Increasing $CO_2$ levels would likely increase both leaf area index and water use efficiency simultaneously. These two changes, combined with increased leaf temperature, will probably not result in any net change in water use per unit land area (Allen 1990). Evaluation of this hypothesis will require developing techniques to extrapolate the experimental work to a forest stand. One approach is to use simulation models. Solomon and West (1986) investigated the impact of greater water-use efficiency on forest population dynamics with a simulation model. They concluded that forest response to elevated $CO_2$ was reduced by the processes of tree regeneration and death. The increase in water-use efficiency was not sufficient to compensate for the probable increase in drought severity expected from a warmer and possibly drier climate.

In another simulation study of forest stand processes, Shugart (1984) found that the primary effect of elevated $CO_2$ was to increase the rate at which gaps in the forest closed. Consequently, forests recovered faster from disturbances and forests with more disturbances were more responsive to additional $CO_2$. "Although ... simulation studies of possible responses of forests to enhanced levels of $CO_2$ are based on simple assumptions and formulations, the indications that population dynamics may override the consequences of $CO_2$ fertilization are interesting. The direct effects of $CO_2$ must therefore be considered within the larger scale consequences of population dynamics and responses of different species to $CO_2$-induced climate change" (Ågren et al. 1991).

## CONCLUSIONS

Climate Induced Changes in Forest Composition and Distribution

Despite the limitations of the models used in the climate change analyses, some overall conclusions can be made concerning climate change impacts on Northwest forests. The foremost of these is that the distribution and composition of forests in Washington and Oregon could change substantially under the GCM scenarios of regional climate change. The Holdridge, climate/forest correlations, and forest gap models (except for the CLIMACS results) all forecast shifts to forests better adapted to warmer and drier conditions. Temperate forests in the Holdridge scenarios are generally restricted to upper elevations and total forest acreage decreases by 5% to 25% depending on the climate scenario used. In central Oregon, total forested area is projected to decrease by almost half under a 5°C warming. Forest zones could move up one complete elevation band under the same degree of warming. Oak woodlands and dry Douglas-fir dominated forests are likely to increase in areal extent, while the more productive western hemlock - Douglas-fir forests will undergo significant contraction. Subalpine and alpine vegetation are likely to be reduced substantially. Declines in moisture availability would decrease forest productivity and long-term timber production.

The forest gap modeling work is in need of additional refinement. ZELIG results do show an upward movement of forest types, and a general decrease in forest biomass. However, the model does not simulate low elevation or dry sites well. Thus, the accuracy of simulations under warmer more xeric conditions is uncertain. ZELIG simulates the dynamics of upper elevational forests better than the lower elevational sites, perhaps because temperature actually does constrain forest growth, as assumed by the model.

Expert judgement suggests that disturbance frequencies (fires and pest/pathogen outbreaks) could increase under warmer conditions. Increased disturbance rates could speed the conversion of forest types and decrease the biological inertia represented by long-lived trees. Forest management practices could have significant impacts on forest response to climate change. Even without disturbance, the ZELIG results suggest that mature trees would be killed under the $2xCO_2$ climate conditions simulated by GCMs.

The major uncertainties in predicting Northwest forest response to climate change can be summarized in five questions: 1) What will be the rate of future climate change? 2) What impact will climate change have on current disturbance regimes of Northwest forests? 3) How will current land use affect the response of forests to climate change? 4) How will increases in $CO_2$ concentrations and shifts in moisture availability affect forest composition and distribution, and 5) What role will forest management play in mitigating climate change impacts on forests? Additional experimental and modeling research will need to focus on these questions in order to improve our ability to predict future changes in the distribution and composition of Northwest forests.

Implications for Forest Management

Climatically induced changes in Northwest forests of the magnitude predicted here raise a number of forest management issues.

1.) How much must current uncertainties in climate predictions and vegetation response be reduced before forest managers feel it is appropriate to implement irreversible management practices to adapt to the predicted climate changes?
2.) How should timber management be changed given current rotation lengths and the possibility of substantial climate change over the period of that rotation? What tree species should be planted, and when should plantations be harvested?
3.) Are there "no regrets" management practices for adapting to climate change that can be implemented now without a substantial cost if climate change does not occur as expected?
4.) How should current strategies at protecting endangered species (e.g. the spotted owl) be altered considering the prospect of large changes in future climate?
5.) How can forest management practices be altered to promote the sequestering of carbon and slow the increase in atmospheric concentrations of $CO_2$?

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**Table 1.** Scientific nomenclature for common tree species in the Pacific Northwest.

| Scientific Name | Common Name |
|---|---|
| *Abies amabilis* | Silver fir |
| *Abies procera* | Noble fir |
| *Abies lasiocarpa* | Subalpine fir |
| *Abies grandis* | Grand fir |
| *Acer macrophyllum* | Big leaf maple |
| *Alnus rubra* | Red alder |
| *Arbutus menziesii* | Pacific madrone |
| *Castanopsis chrysophylla* | Golden chinkapin |
| *Chamaecyparis nootkatensis* | Port-Orford-Cedar |
| *Larix occidentalis* | Western larch |
| *Libocedrus decurrens* | Incense cedar |
| *Lithocarpus densiflorus* | Tanoak |
| *Picea engelmannii* | Engelmann spruce |
| *Picea sitchensis* | Sitka spruce |
| *Pinus lambertiana* | Sugar pine |
| *Pinus monticola* | Western white pine |
| *Pinus ponderosa* | Ponderosa pine |
| *Pseudotsuga menziesii* | Douglas-fir |
| *Quercus chrysolepis* | Canyon live oak |
| *Quercus garryanna* | Oregon white oak |
| *Thuja plicata* | Western red cedar |
| *Tsuga heterophylla* | Western hemlock |
| *Tsuga mertensiana* | Mountain hemlock |

**Table 2.** Potential changes in mean January, July, and annual temperatures and total annual precipitation under double $CO_2$ climate conditions at selected gridpoints as simulated by four General Circulation Models.[1] The gridpoints are situated in the Willamette Valley, Oregon. Other gridpoints in the Northwest show similar changes.

| GCM/ Climate Variable | OSU 46.0°N, 120.0°W | GISS 43.0°N, 120.0°W | GFDL 42.2°N, 120.0°W | UKMO 42.5°N, 123.8°W |
|---|---|---|---|---|
| Mean January Temperature Change (°C) | +0.8 | +6.6 | +3.2 | +6.3 |
| Mean July Temperature Change (°C) | +2.1 | +3.3 | +5.2 | +9.3 |
| Mean Annual Temperature Change (°C) | +2.3 | +5.0 | +4.6 | +6.7 |
| Annual Precipitation Change | +4% | +23% | +2% | +17% |

[1] The grid cell sizes (latitude and longitude) for each of the general circulation models are: OSU - 4°x5°; GISS - 7.83°x10.0°; GFDL - 4.4°x7.5°; UKMO - 5.0°x7.5°.

**Table 3.** Comparison of the impact of climate change on mean annual temperature and mean annual growing degree-days. The temperature data are from historical records (NOAA 1989a,b) or from $2xCO_2$ climate scenarios generated by the OSU and GISS GCMs. The $2xCO_2$ temperature scenarios were generated by multiplying the historical monthly mean temperature by the ratio of the GCM-simulated $2xCO_2$ monthly mean temperature to the GCM-simulated $1xCO_2$ monthly mean temperature. Mean annual growing degree days were calculated from the WEATHR routine in the ZELIG simulation model (Urban 1990). The length of the historical record from which the mean temperatures were calculated is given in parentheses.

| Location | Current Temp. (°C) | OSU $2xCO_2$ Temp. (°C) | GISS $2xCO_2$ Temp. (°C) | Current Degree-Days | OSU $2xCO_2$ Degree-Days | GISS $2xCO_2$ Degree-Days |
|---|---|---|---|---|---|---|
| Forks, WA | 9.7 (68) | 11.8 | 13.6 | 1636 | 2317 | 2926 |
| Rainier, WA | 3.1 (47) | 5.4 | 8.0 | 502 | 865 | 1360 |
| Longview, WA | 10.8 (65) | 13.0 | 15.9 | 2013 | 2741 | 3790 |
| Astoria, OR | 10.4 (36) | 12.5 | 15.4 | 1793 | 2548 | 3606 |
| H.J. Andrews, OR | 9.8 (13) | 12.1 | 14.9 | 1779 | 2501 | 3413 |
| Crater Lake, OR | 3.2 (57) | 5.3 | 8.1 | 604 | 963 | 1454 |
| Gold Beach, OR | 11.6 (60) | 13.6 | 16.7 | 2234 | 2922 | 4076 |
| Ashland, OR | 11.1 (104) | 13.1 | 16.2 | 2208 | 2809 | 3888 |

**Table 4.** Comparison of the impacts of climate change on annual precipitation and annual potential evapotranspiration (PET). The current precipitation data are from historical records (NOAA 1989a,b) from the OSU and GISS GCMs, while current PET was calculated from the WEATHR routine in the ZELIG simulation model (Urban 1990, Urban et al. 1990) using the Thornthwaite method. The ratios for precipitation and PET are ($2xCO_2$ GCM prediction)/($1xCO_2$ GCM prediction). See text for discussion of how $2xCO_2$ precipitation scenarios were created. The length of the historical record from which the mean annual precipitation was calculated is given in parentheses.

| Location | Current Prec. (cm) | OSU Prec. Ratio | GISS Prec. Ratio | Current PET (cm) | OSU PET Ratio | GISS PET Ratio |
|---|---|---|---|---|---|---|
| Forks, WA | 302 (79) | 1.01 | 1.27 | 62.8 | 1.09 | 1.15 |
| Rainier, WA | 289 (53) | 1.03 | 1.22 | 42.5 | 1.16 | 1.34 |
| Longview, WA | 117 (65) | 1.01 | 1.22 | 66.0 | 1.09 | 1.24 |
| Astoria, OR | 177 (36) | 1.00 | 1.23 | 63.9 | 1.08 | 1.21 |
| H.J. Andrews, OR | 142 (13) | 1.03 | 1.23 | 62.8 | 1.10 | 1.23 |
| Crater Lake, OR | 170 (61) | 1.00 | 1.24 | 41.4 | 1.16 | 1.36 |
| Gold Beach, OR | 210 (69) | 1.02 | 1.23 | 65.4 | 1.07 | 1.22 |
| Ashland, OR | 48 (111) | 1.01 | 1.23 | 67.0 | 1.09 | 1.27 |

**Table 5.** Areal extent of Holdridge life zone classes before and after a double $CO_2$ climate change (data from Smith et al., 1991) for the Pacific Northwest (Idaho, Oregon, Washington). Area (thousands of $km^2$) and percent change (in parentheses) from current conditions are given for each life zone category.

| Area Predicted for Each Climate Scenario/Life Zone Category | Current Climate | OSU Scenario | GISS Scenario | GFDL Scenario | UKMO Scenario |
|---|---|---|---|---|---|
| Cold Desert | 77 | 69 (-10) | 9 (-88) | 56 (-27) | 2 (-97) |
| Hot Desert | 0 | 4 | 6 | 23 | 15 |
| Steppe | 215 | 225 (5) | 185 (-14) | 170 (-21) | 111 (-49) |
| Chapparral | 4 | 37 (757) | 144 (3192) | 148 (3301) | 255 (5760) |
| Boreal (Subalpine) Forests | 130 | 63 (-51) | 26 (-80) | 15 (-89) | 0 (-100) |
| Temperate Forests | 186 | 223 (20) | 171 (-8) | 142 (-24) | 93 (-50) |
| Warm Temperate Forest | 2 | 15 (571) | 95 (4310) | 78 (3521) | 110 (4986) |
| Tropical Semi-Arid Forest | 0 | 0 | 2 | 2 | 30 |
| Tropical Seasonal Forest | 0 | 0 | 0 | 0 | 18 |
| Tropical Dry Forest | 0 | 0 | 0 | 2 | 4 |
| Total Forest Area | 318 | 301 (-5) | 292 (-8) | 239 (-25) | 254 (-20) |

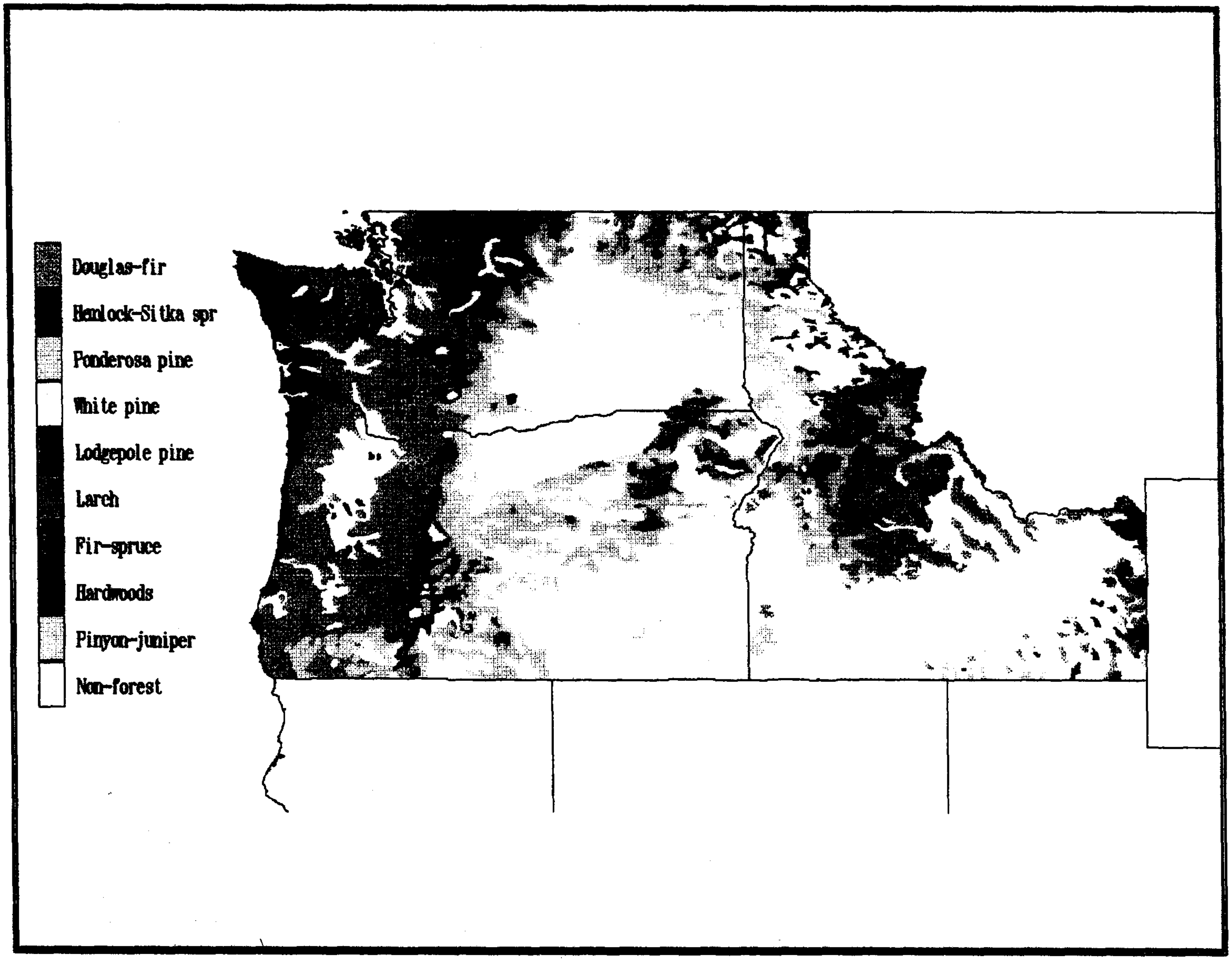


Fig. 1. Forest types in the Pacific Northwest (USDA 1970). The Douglas-fir zone is essentially equivalent to the western hemlock zone described in the text.

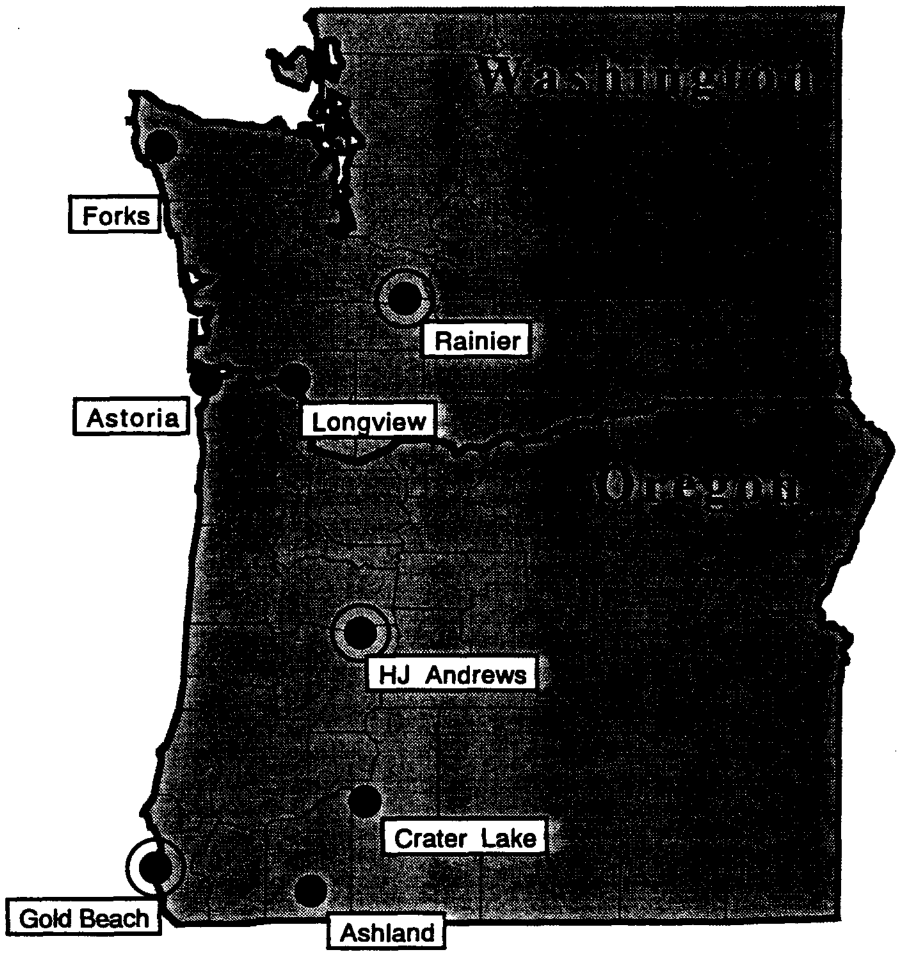


Fig. 2. Location of climate stations listed in Tables 3 and 4. The ZELIG forest gap model was run at sites with a double circle.

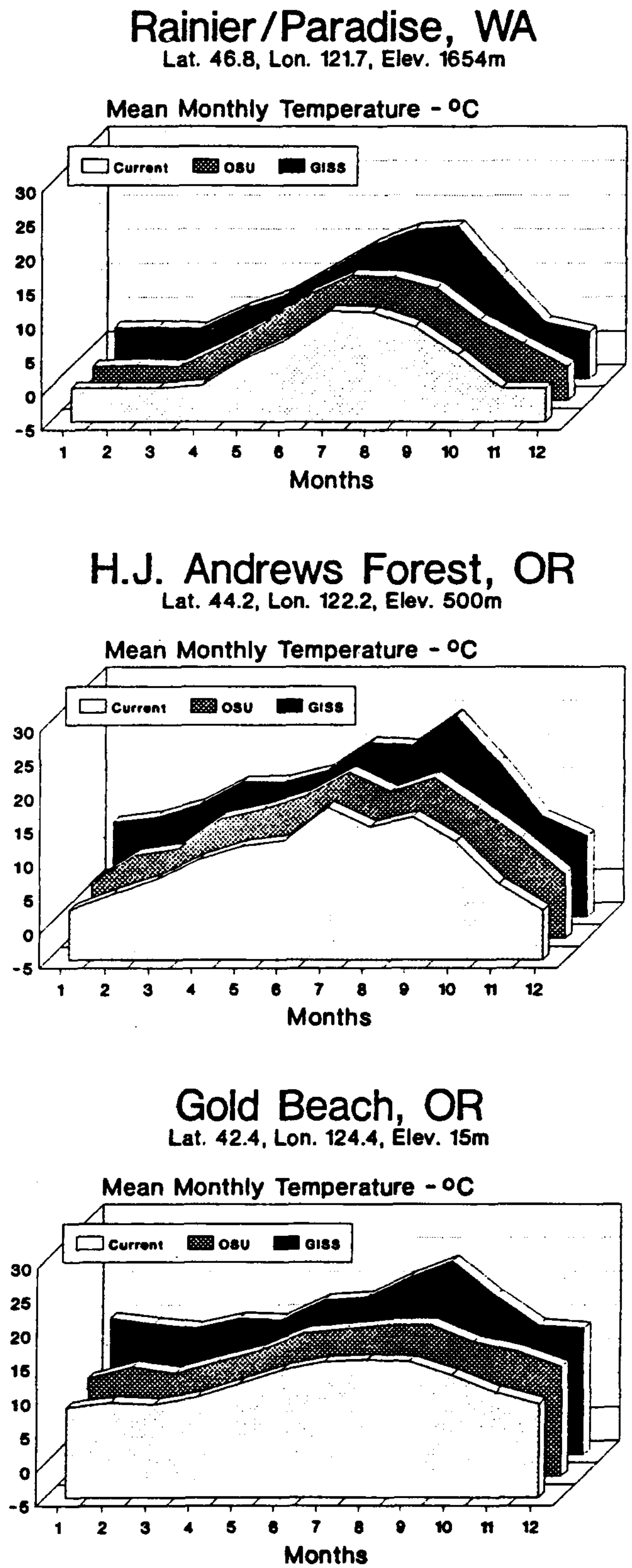


Fig. 3. Long-term mean and predicted future mean monthly temperatures for three sites in the Northwest (NOAA, 1989a,b). Scenarios of the future temperature regimes at these sites were generated using output from the OSU and GISS climate simulations of double $CO_2$ climate conditions.

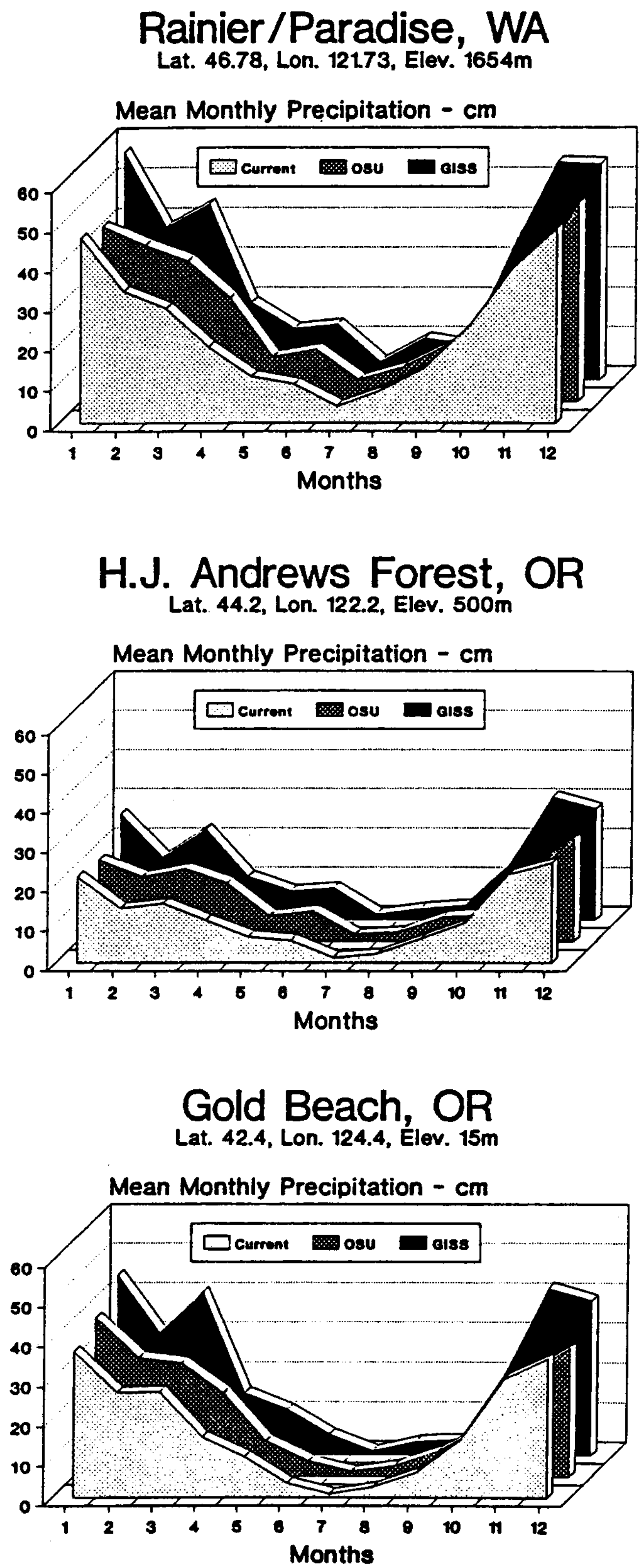


Fig. 4. Long-term mean and predicted future mean monthly precipitation for three sites in the Northwest. Scenarios of the future precipitation regimes at these sites were generated using output from the OSU and GISS climate simulations of double $CO_2$ climate conditions.

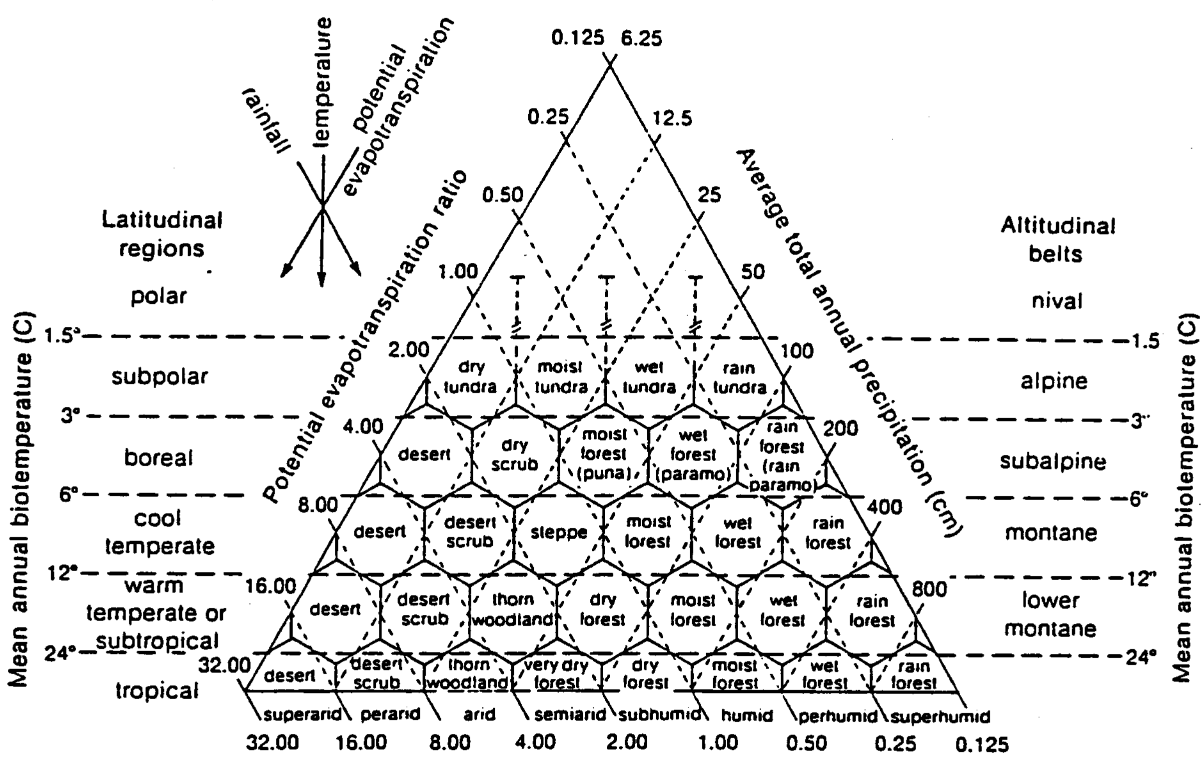


Fig. 5. Holdridge life-zone classification system of global biomes (Holdridge, 1967).

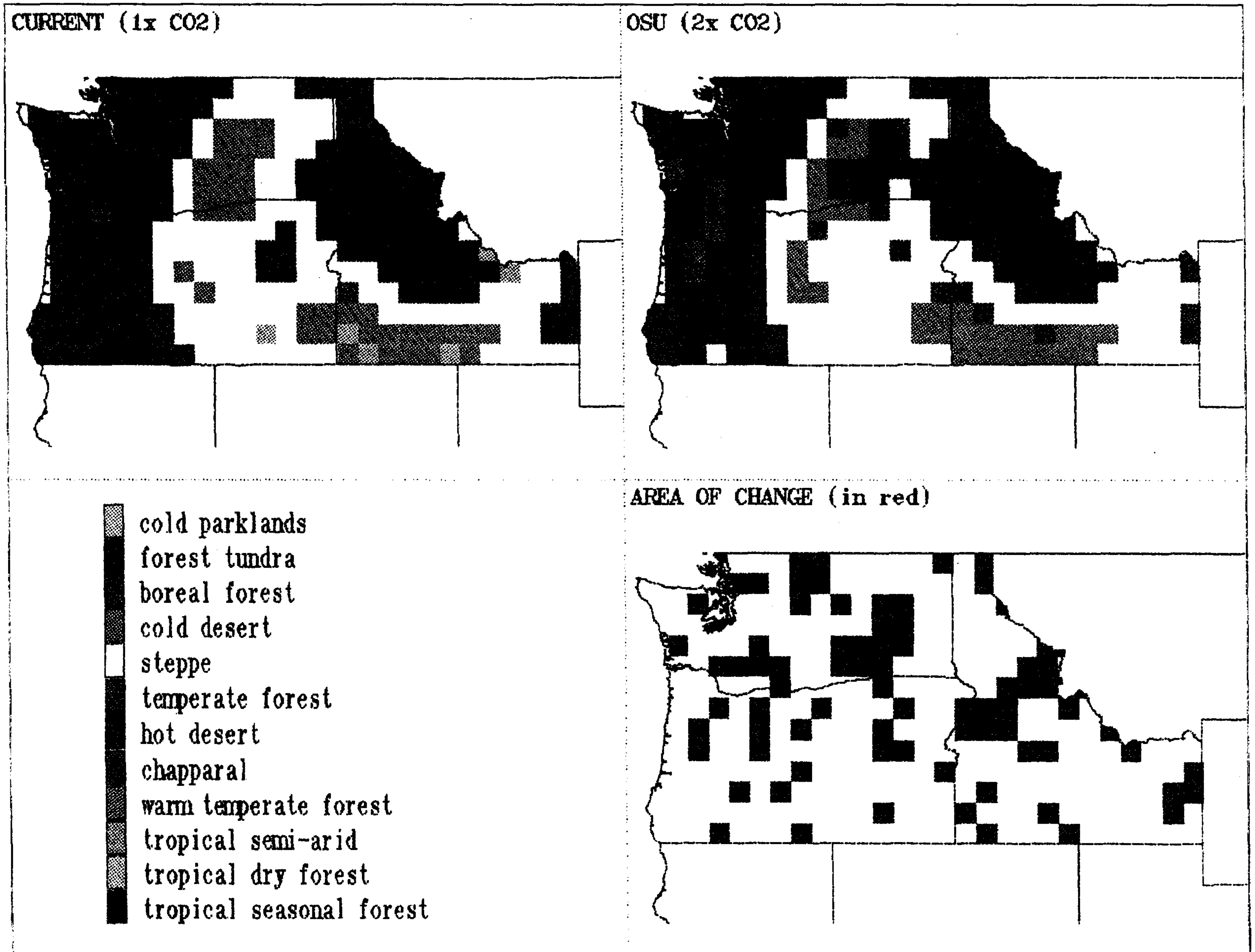


**Fig. 6. Vegetation redistribution in the Pacific Northwest (Washington, Idaho, and Oregon) under the OSU climate scenario using the Holdridge life-zone classification system (Smith et al., 1991). The map in the upper left shows the current vegetation of the region as simulated using the Holdridge system, the map at the upper right shows the potential future distribution of vegetation under the OSU climate scenario, and the map on the lower right shows those areas in the region (in red) where the vegetation changes from one Holdridge type to another under the future climate scenario.**

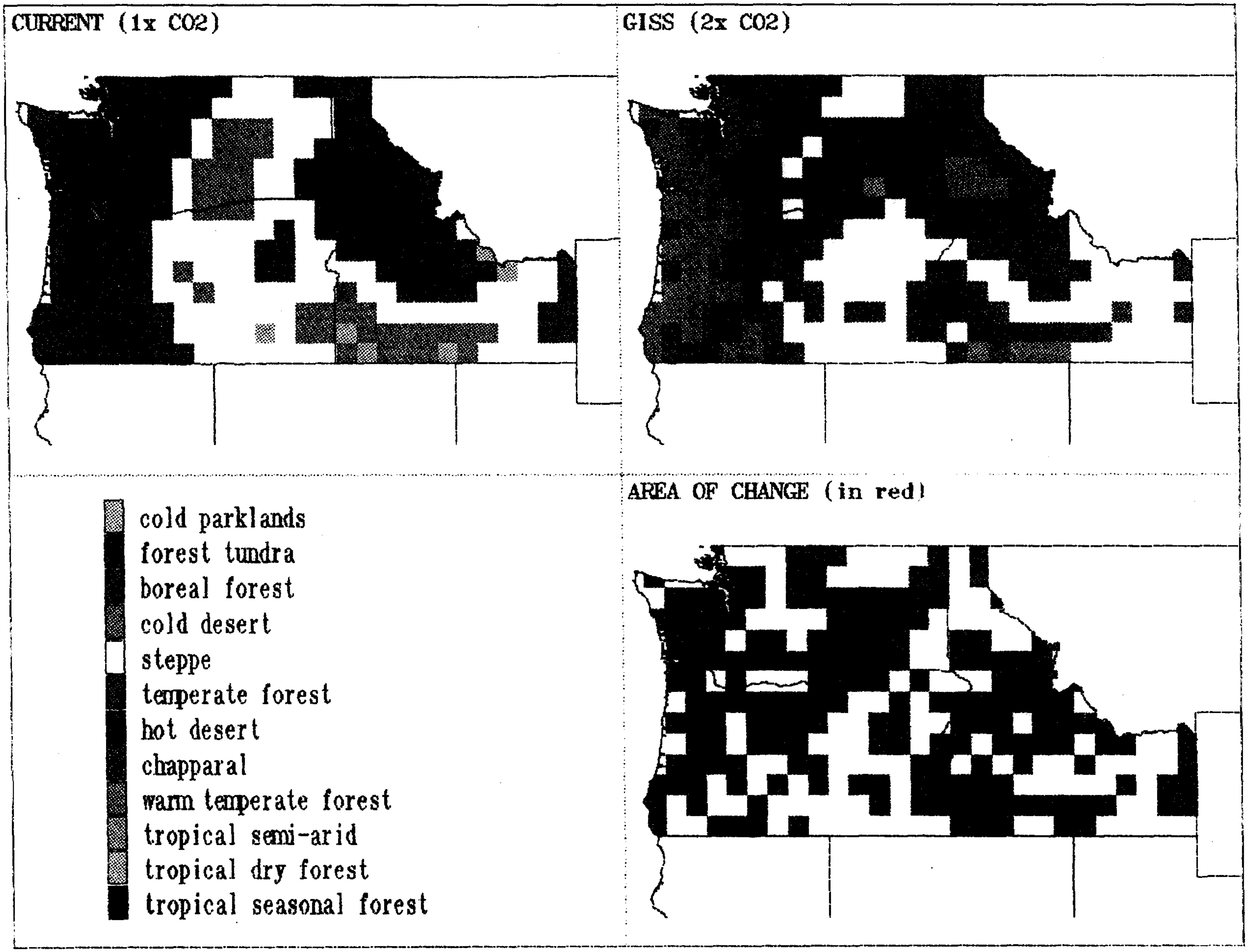


**Fig. 7. Vegetation redistribution in the Pacific Northwest (Washington, Idaho, and Oregon) under the GISS climate scenario using the Holdridge life-zone classification system (Smith et al., 1991). The map in the upper left shows the current vegetation of the region as simulated using the Holdridge system, the map at the upper right shows the potential future distribution of vegetation under the GISS climate scenario, and the map on the lower right shows those areas in the region (in red) where the vegetation changes from one Holdridge type to another under the future climate scenario.**

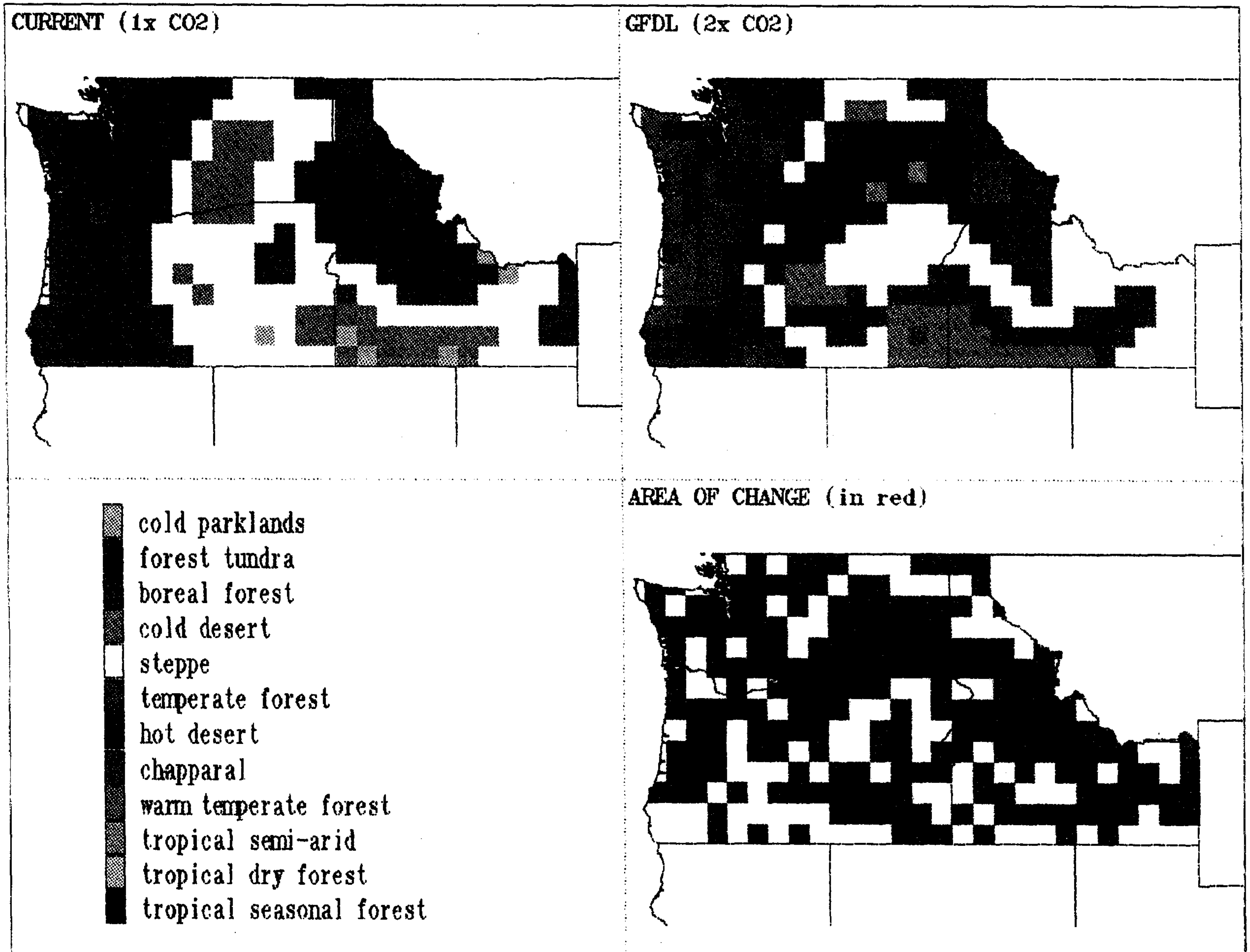


Fig. 8. Vegetation redistribution in the Pacific Northwest (Washington, Idaho, and Oregon) under the GFDL climate scenario using the Holdridge life-zone classification system (Smith et al., 1991). The map in the upper left shows the current vegetation of the region as simulated using the Holdridge system, the map at the upper right shows the potential future distribution of vegetation under the GFDL climate scenario, and the map on the lower right shows those areas in the region (in red) where the vegetation changes from one Holdridge type to another under the future climate scenario.

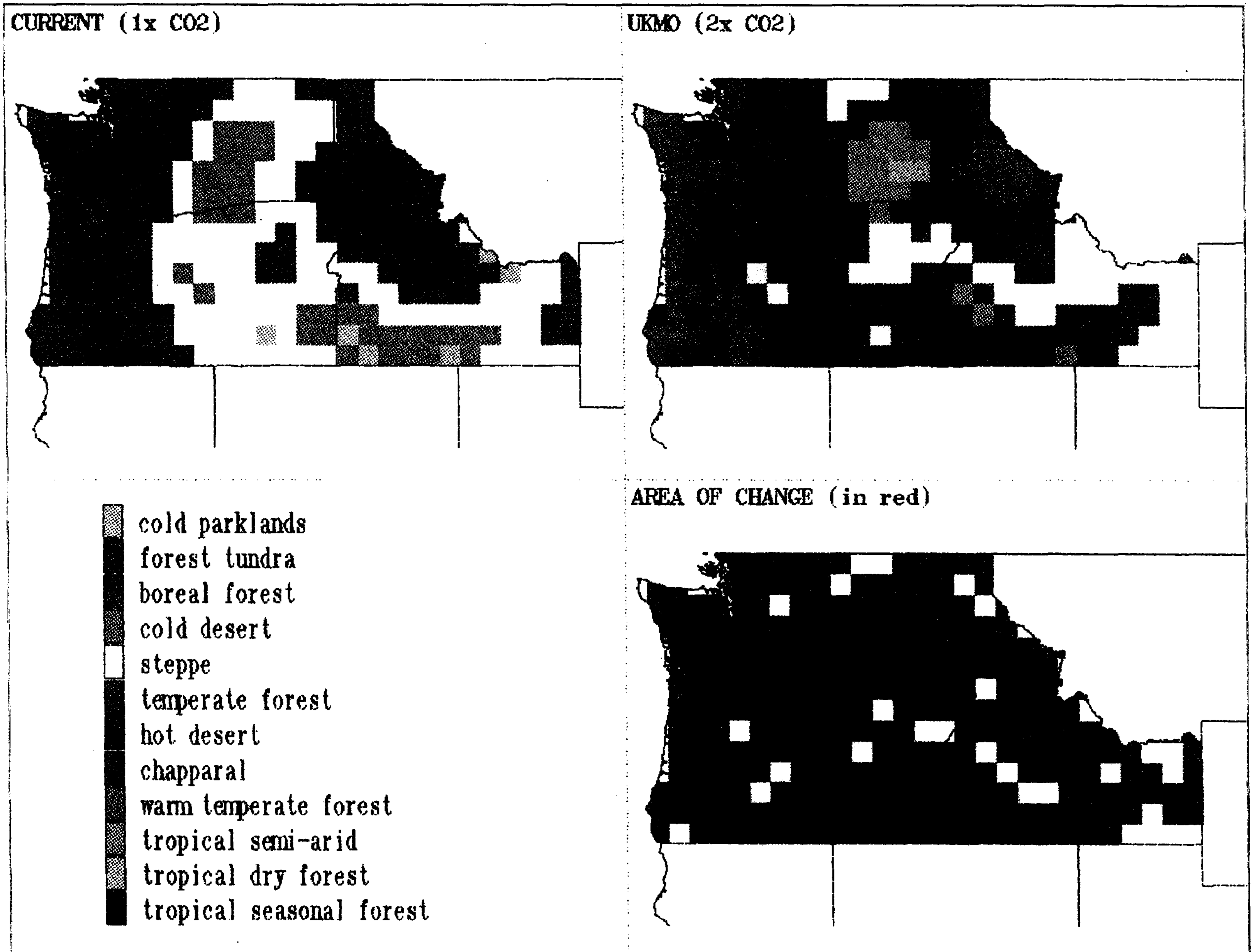


Fig. 9. Vegetation redistribution in the Pacific Northwest (Washington, Idaho, and Oregon) under the UKMO climate scenario using the Holdridge life-zone classification system (Smith et al., 1991). The map in the upper left shows the current vegetation of the region as simulated using the Holdridge system, the map at the upper right shows the potential future distribution of vegetation under the UKMO climate scenario, and the map on the lower right shows those areas in the region (in red) where the vegetation changes from one Holdridge type to another under the future climate scenario.

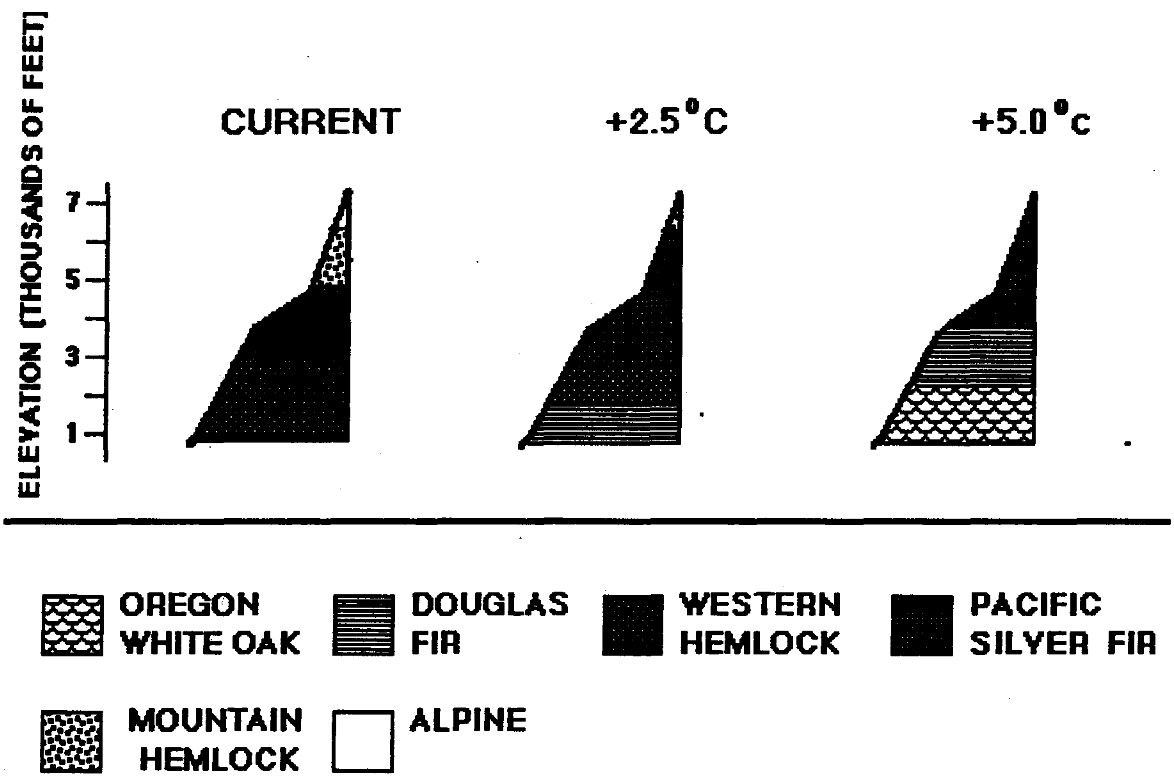


Figure 10. A schematic drawing showing potential upward shifts in forest zones on the westslope of the central Oregon Cascades (latitude 44° 30'N) under a 2.5°C warming and a 5°C warming using current correlations of forest types and climate to infer the future distribution of these same types (Franklin et al., 1991). Quantitative estimates of the area in each of these forest types are depicted in Figure 11.

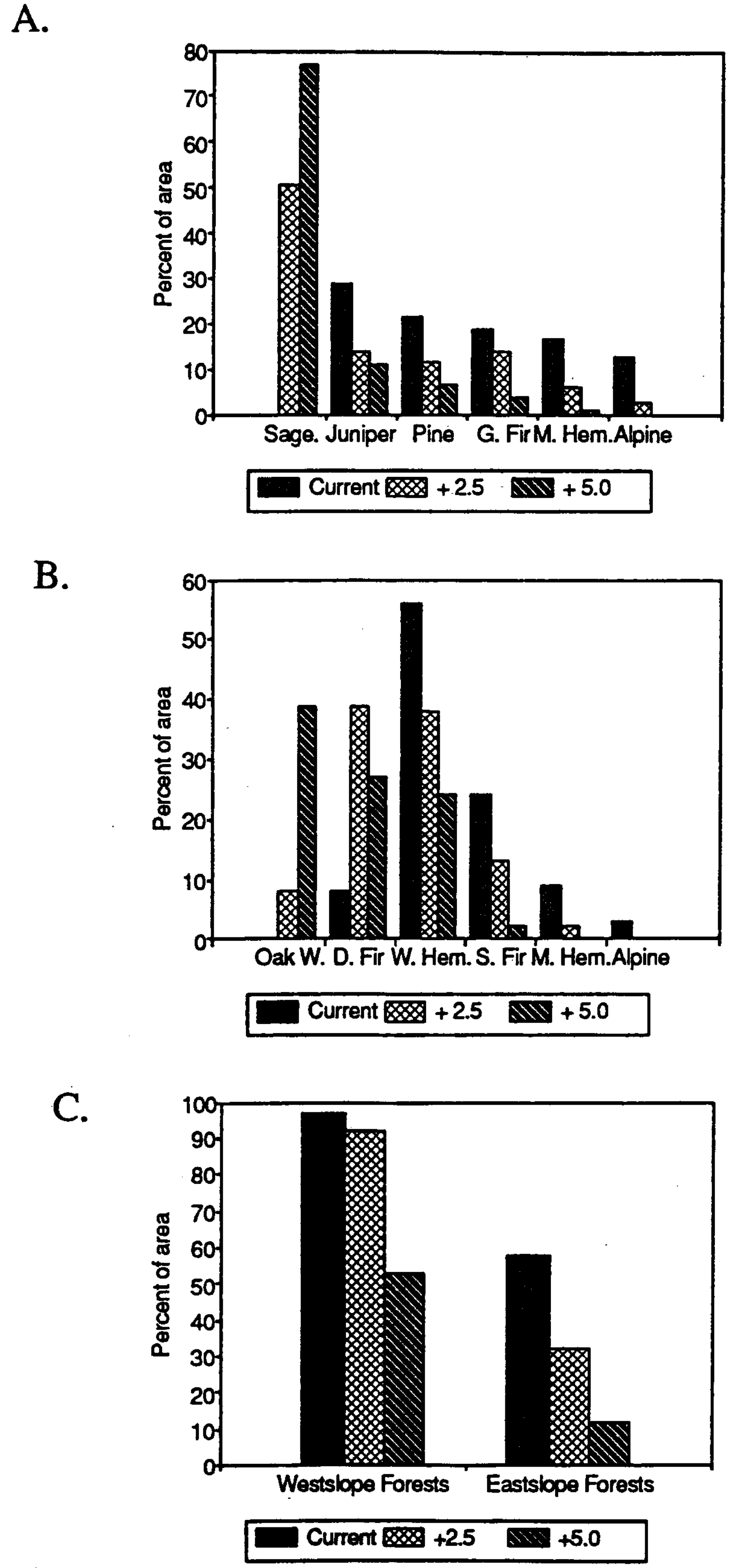


Figure 11. Percent of area occupied by current vegetation types in the central Oregon Cascade Range under current, 2.5°C warmer, and 5.0°C warmer climate conditions (Franklin et al. 1991). A. Eastslope vegetation changes. B. Westslope vegetation changes. C. Changes in total forest cover on the eastslope and westslope. Key to abbreviations: Sage. = Sagebrush steppe, Pine = ponderosa pine, G. Fir = grand fir, M. Hem. = mountain hemlock, Oak W. = oak woodland, D. Fir = Douglas-fir forest series, W. Hem. = western hemlock series, S. fir = silver fir.

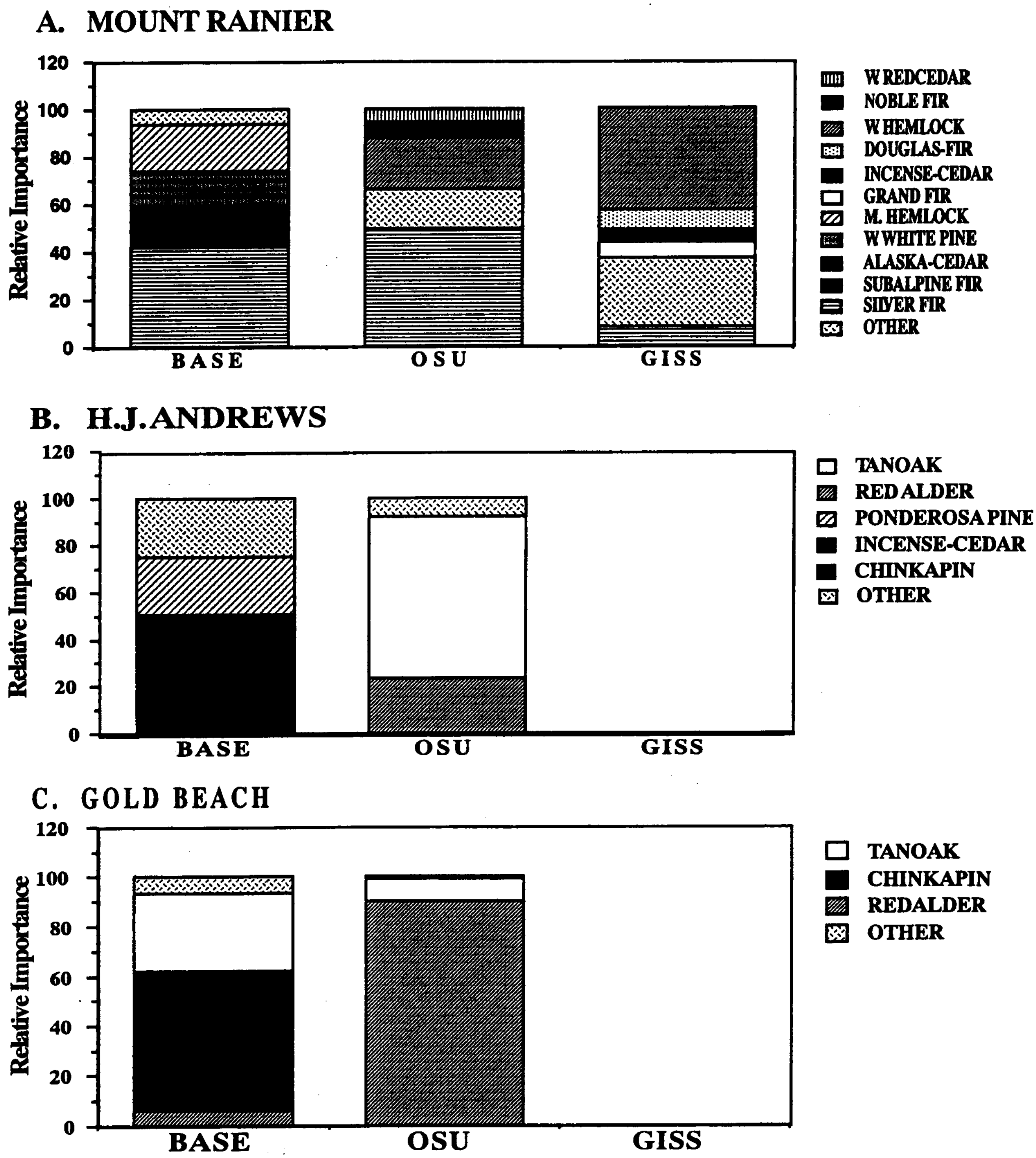


Figure 13. Potential changes in the relative importance of forest tree species at A. Mt. Rainier, WA, B. H.J. Andrews, OR, and C. Gold Beach, OR, as simulated by ZELIG for current (Base) climate and OSU and GISS climate scenarios. (Urban 1990, Urban et al. 1990, 1991). Location of sites is given in Fig. 2.