

May 28, 1991 Draft - Do not quote or cite

POTENTIAL IMPACTS OF CLIMATE CHANGE ON PACIFIC NORTHWEST FORESTS

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TABLE OF CONTENTS

FINDINGS	i
INTRODUCTION	1
CURRENT STATUS OF NORTHWEST FORESTS	1
Common Forest Types	1
Current Land Use	2
Future Resource Condition Without Climate Change	2
SENSITIVITY OF FORESTS TO CURRENT AND FUTURE CLIMATE	3
Current Climate	3
Adaptation of Forests to Current Climate	4
Sensitivity to Future Climate Change	4
METHODOLOGY	5
Generation of Climate Scenarios	5
Vegetation Modeling - Application of the Holdridge Life-Zone Classification	6
Vegetation Modeling - Local Climate-Forest Zone Correlations	7
Vegetation Modeling - Forest Gap Models	7
Carbon Model Results	9
RESULTS	9
Holdridge Vegetation Scenarios	9
Simulation of Current Vegetation	9
Estimated Vegetation Change	9
Assumptions/Limitations	10
Local Climate-Forest Zone Correlations	10
Forest Gap Models - CLIMACS Results	11
Simulation of Current Forests	11
Estimated Changes in Forest Compositions	11
Assumptions/Limitations	11
Forest Gap Models - ZELIG Results	12
Simulations of Current Vegetation	12
Estimated Changes in Forest Composition	13
Assumptions/Limitations	14
Potential Changes in Carbon Storage	14
Expert Judgement - Effects of Climate Change on Forest Disturbances	15
Major Uncertainties	16
Transient Dynamics	16
Direct Effects of CO ₂	17
CONCLUSIONS	19

May 28, 1991 Draft - Do not quote or cite

Climate Induced Changes in Forest Composition and Distribution	19
.....	19
Implications for Forest Management	19
ACKNOWLEDGEMENTS	21
LITERATURE CITED	22

FINDINGS

Trace gas induced climate change could 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 would 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, Douglas-fir dominated forests would increase in area, whereas the more productive western hemlock forests would decrease. Forest vegetation zones would increase in elevation from 500 to 1000m. Alpine and subalpine forests could disappear from all but the highest elevations in the region.

Forest disturbances such as fire and pest/pathogen outbreaks would likely increase in frequency, speeding vegetation change in response to climate change.

There are two key limitations to the data presented here. First, the transient (time-dependent) dynamics of change have

not been adequately addressed. How forest dynamics respond to a rapidly changing but variable climate is uncertain. Second, the direct effects of enhanced CO₂ concentrations on forest species growth has not been considered in any of the modeling simulations. Laboratory experiments suggest the potential for increased drought tolerance by individual plants under higher CO₂ concentrations. The landscape scale impacts of higher CO₂ concentrations are uncertain.

Forest managers are thus presented with a difficult problem. Specifically, how should current forests be managed given 1) our uncertainty as to 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). Biomass storage is higher than any other vegetation type in the world (Waring and Franklin 1979, Franklin 1988, Harmon et al. 1990). In sum, these forests are unique among north temperate forest types, in which deciduous trees are usually the dominant life-form. Besides their intrinsic value as unique ecological systems, Northwest forests serve as an important source of timber and are a focus of the 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 chapter is to summarize our 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 of land in Washington, Oregon, and Idaho, or about 46% of the region (Figure 1, Table 1a,b). Forests occupy higher elevations east of the Cascades, and dominate the land west of the Cascades. Douglas-fir (see Table 2 for scientific nomenclature) and western hemlock are the most important trees in forests ranging from sea-level to 700-1000 m west of the Cascades (Franklin 1988). Douglas-fir typically dominates younger forest stands, with hemlock and western red cedar increasing in importance after 400-600 years². Grand fir and western white pine ^{are} can be minor components of forests west of the Cascades. In central Oregon, incense cedar, sugar pine, and ponderosa pine may occur. Hardwoods are rare in these forests, occupying recently disturbed sites or riparian zones. Big leaf maple and red alder are the most common hardwood species. On drier sites, Pacific madrone, golden chinkapin and Oregon white oak are common (Franklin 1988). Understory composition varies widely in this forest zone, controlled generally by moisture availability (Franklin 1988).

Along the Pacific coast, a narrow band of Sitka spruce - western hemlock forest prevails. Sitka spruce is only found within a few tens of kilometers of the coast, forming pure stands along the coast (or with lodgepole pine) because of its salt tolerance. Hemlock is usually more abundant, however (Franklin 1988).

At higher elevations in the Cascades and Olympic Mountains, mixed conifer forests occur (Franklin 1988). Common tree species include silver fir, western hemlock, noble fir, Douglas-fir, western red cedar, and western white pine. At higher elevations and towards the interior,

lodgepole pine, subalpine fir, Englemann spruce, western larch, mountain hemlock, and Port-Orford-Cedar can be present. Western hemlock often forms pure stands at the highest elevations in the Cascades and Olympic mountains that can support forests.

Complex geology and steep gradients in moisture and temperature make the Klamath Mountains in southwestern Oregon and northern California the most diverse forested region in the study area (Whittaker 1960, Franklin 1988). Mixed conifer and evergreen hardwood forests are typical here. Douglas-fir is usually the dominant conifer, and the evergreen trees tanoak, canyon live oak, Pacific madrone, and golden chinkapin can form a hardwood understory.

Carbon storage in old growth 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). Productivity in eastern Oregon forests (east of the Cascade crest) is significantly lower.

In contrast to conifer forests elsewhere in North America, disturbances are infrequent in Pacific Northwest forests. The natural fire rotation in these forests is about 400-500 years and tends to be shorter in the southern part of the range (Franklin 1988). Wind storms can produce widespread tree mortality, but are of lesser importance in the Cascades than along the coastal mountains. Pest and pathogen outbreaks are not as frequent as in other western conifer forests (Franklin 1988).

Current Land Use

About 75% of the forest land in the Northwest are managed for timber production (Table 1, USDA 1989). Over the region, about 63% of the timberland is publically owned, although in Washington State timberland is equally divided between public and private ownership. Forest industry owns about half of the private forest lands in the Northwest.

Currently timberlands are in transition from un^amanged 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). Rotation length is about 80-100 years on National Forest lands (Swanson et al. in press).

Future Resource Condition Without Climate Change

Even without climate change management of forests will face increasing challenges in the future. Increasing demands are being placed on the 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 challenge will be developing a strategy to protect the northern spotted owl (USDA FS 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.

Another 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. Franklin and Foreman (1987) analyze the effects of various cutting strategies on landscape patterns. An important result was that the widely used practice of dispersed 10-20 ha cuts through a virgin landscape will eventually fragment the remaining forests into smaller and smaller contiguous tracts. This effectively reduces the amount of interior forest available as habitat for old growth dependent species. Techniques at modeling landscape patterns have been developed to help evaluate alternative cutting patterns (Hemstrom 1990, Cissel 1990, 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, in this region, grow under a wide range of temperature and moisture regimes. Mean annual temperature range is about 5° C, while precipitation varies about an order of magnitude (approximately 300 cm) (Franklin et al., in press).

In general, both summer and winter temperatures decrease from south to north (Fig. 2). The north to south temperature gradient is steeper in the winter than the summer. Focusing again on the region west of the Cascade crest, at Gold Beach, OR the mean January temperature is 8.3° C while at Forks, WA it is 3.8° C. In the summer, mean July temperatures are 18.0° C at Andrews, and 15.7° C at Forks, WA. Similarly, there is a large decrease in the duration of the growing season which ranges from 365 days at Gold Beach, OR to 281 days at Forks, WA. Similarly, the growing season becomes shorter and the temperatures lower as the elevation increases. Summer (mean monthly) temperatures only reach 13.2° and 12.4° C at Rainier/Paradise, WA and Crater Lake, OR with 5 to 6 months displaying mean monthly temperatures below 0° C.

There is a distinct seasonality in precipitation with the winters tending to be wet and the summers dry (Figure 3). Depending on the temperature and elevation, the precipitation falls as either rain or snow; significant snow pack occurs at higher elevations. During the winter, monthly precipitation ranges from 40 to 80 cm, while during the summer months precipitation can be less

than 10 cm/month. There are stronger orographic and elevational influences on precipitation than a south to north influence. Rain shadow effects are particularly evident east of the crest of the Olympic Mountains and Cascade Mountains.

Adaptation of Forests to Current Climate

The strong seasonality of climate 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 are summarized by Waring and Franklin (1979) and 1) include the ability to photosynthesize under the 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's broken during evaporative stress (whereas many hardwood species can not; Sucoff 1969, Burke et al. 1976, Sakai 1983).

Within the region soil moisture and temperature are important controls of ecotones between forest types (Daubenmire 1943, Zobel et al. 1986, Franklin 1988). Lower elevational zones are controlled primarily by soil moisture, whereas upper elevational zones are controlled by temperature. Snowpack and wind can be important controls at uppermost elevations in the Cascades and Olympic Mountains (Scott 1980). Also, Leverenz and Lev (1987) point out the seed chilling requirement needed by Douglas-fir for successful regeneration in coastal regions.

Sensitivity to Future Climate Change

A logical extension of the hypothesis that climate controls the dominant vegetation patterns in the region is simply that future climate change will affect regional vegetation patterns. The key question is: how much can climate change before major vegetation redistribution takes place? One way to answer this is to look at the response of vegetation to past climate variation. 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 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) (Brubaker 1988) during which time the vegetation was much different from today's. Douglas-fir was more important than today in western Washington, and oak savanna extended north of its present limit in the Willamette Valley in Oregon to the southern part of the Puget Trough (Barnosky et al. 1987). Thus it appears that climate changes of greater than 2° C will likely 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; Franklin 1988; Brubaker 1986, Franklin et al. in press). Adverse climate conditions may eliminate seedling establishment and sexual reproduction, while mature trees survive for several centuries. Trees which can reproduce asexually may persist "out of equilibrium" with climate for thousands of years (e.g. Neilson and Wullstein 1983). The key definition that needs to be made here is "adverse". It most certainly has an upper and lower bound in this context, since mature trees can be killed by severe climate conditions as well. Unfortunately, the autoecological databases for making such a determination are too incomplete at this time for defining environmental tolerances of seedlings and mature trees of many species in the Northwest. However, modeling exercises using forest gap models (discussed below) may help define the term for certain species.

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. As will be described, the modeling analyses are complimentary, as no single vegetation model can provide the specific detail and geographic context needed in an impacts assessment. The specific limitations and assumptions of the specific modeling analyses will be described in the results sections. Also, expert opinions on climate change impacts (e.g. Franklin et al. in press) are also discussed in the results section.

Generation of Climate Scenarios

Four low resolution general circulation models (GCMs), OSU (Schlesinger and Zhao 1989), GISS (Hansen et al. 1983), GFDL (Manabe and Wetherald 1987), and UKMO (Wilson and Mitchell 1987) were used to project future climate conditions assuming a doubling of "current" ambient CO₂ concentrations. Because the grid sizes of each model (typically about 4° latitude by 5° longitude) is large relative to the area of the Pacific Northwest, we can not expect these models to exactly reproduce the current or projected climate but rather to provide insight into changes over broad regions when the atmospheric CO₂ is increased (Jenne, 1988). To convert the low resolution GCM output to specific locations, the ratios of 2X:1X CO₂ model runs were used to multiple current mean monthly temperature and precipitation for each location. Temperatures were first converted to °K before calculating the ratios. Current climate data for selected locations in Washington and Oregon was provided by Charles B. Halpern, Department of Forest Science, Oregon State University from long-term NOAA summaries. The length of the time-series used to create the mean values varies with location, and ranged between 30 and 60 years.

The overall effect of climate change in the Pacific Northwest is that forests will become significantly warmer. The GCMs project a 2° to 5° C increase in annual mean temperatures (Table 3) with projected temperatures decreasing from south to north. 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 (Figure 2). Growing degree days, a measure of the cumulative increase in temperature over the growing season, is projected to increase significantly (Table 3). The OSU GCM projects a 37 to 73% increase in growing degree/days while the GISS model projects significantly more warming (83 to 133%).

Under the projected climate change, there are no seasonal shifts in precipitation; the pattern of relatively dry summers and wet winters will persist (Figure 3). Although the seasonality is maintained, the proportions of rain and snow may change from the current conditions. Two of the GCMS (OSU and GFDL) predict unchanged annual precipitation, while the other two (GISS and UKMO) predict about 20% greater annual precipitation. In terms of the impact on vegetation, changes in soil moisture is of greatest interest. This depends in a large part on potential evapotranspiration (PET), estimates of which are listed in Table 4. The projected changes in PET are dependent on the method of calculation and must be viewed as preliminary estimates at this time (Marks 1990). Overall, the UKMO scenarios present the largest change from current conditions, particularly the large increases in summer temperature.

The climates projected from the GCMs represent a significant shift from present conditions. When viewed in a south to north transect, the climatic change is equivalent to shifting current climates from 200 to 500 km north from the present locations, i.e., moving the climate of northern California into northern Oregon and the climate of northern Oregon into northern Washington (Franklin et al., in press). Similarly, when these changes are viewed from an elevational perspective, it is equivalent to moving current climatic conditions at the base of mountain 500 to 1000 m upward (Franklin et al., in press).

Vegetation Modeling - Application of the Holdridge Life-Zone Classification

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

The Holdridge Life-Zone classification system relates major vegetation formations with 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 (Figure 4). Smith and Leemans (1990) applied the

Holdridge classification system to a gridded, global database of mean monthly temperature and mean annual precipitation (Leemans 1990) for current climate, and simulated future climate using GCM output described above. The climate data base has a resolution of 0.5°, which consequently is the resolution of the vegetation scenarios.

Vegetation Modeling - Local Climate-Forest Zone Correlations

Franklin et al. (in press) used correlations of climate and forest zonation in the central Oregon Cascades (Franklin 1988) to estimate changes in the areal extent of forest communities under two climate change scenarios. In particular, the current temperature for a particular elevation was assumed to increase by either 2.5° and 5° C. The current relationship between temperature and forest types were used to define the new elevational bands the forest types would occupy under these two scenarios. Then the areal extent of the forest zones at their new elevations was determined using a 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 m²) 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 a 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 Franklin 1989, Urban and Shugart 1989, Bonan et al. 1990). The models simulate tree growth for every individual 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 behavior of each tree species included in the model. Growth rates or other processes 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 for application to the Northwest, specifically for 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, making mortality dependent on successional class of the species, and incorporating natural disturbances and clear-cut logging (Dale and Hemstrom 1984, Dale et al. 1986). Twenty-one tree species are included in the model. The model was run assuming a 5° C warming in northwest Oregon, using data from Cascade Head on the Oregon coast. The climate change scenario was applied to a typical stand structure of a forest 140 years old at Cascade Head.

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, unpublished report). The major effort in implementing the model in the Northwest was developing a set of species parameters (e.g. growing degree day limits) describing life history and growth characteristics for each Northwest tree species. In contrast to eastern United States where relief is substantially less, tree species in the mountains of the Northwest often have upper and lower elevational range limits. Correlations of climatic variables and these range limits were thus established at a number of latitudinal bands from northern California into British Columbia. Because of sparse climate data, regional regression models were developed to predict mean monthly temperature (Urban et al. 1990). Substantial latitudinal variation occurs in the climatic limits of some of the major species in the region (to be discussed more later).

ZELIG was tested initially at the H.J. Andrews LTER site (44.2° N, 122.2° W) in the central Oregon Cascades because of large amount of forest stand data available for model verification. The model was applied at three elevations, 500m, 1000m, and 1500m. The climate parameters defining the range limits of species at the Andrews latitude (44° N) were used in the model run. Model simulations started from bare ground (in contrast to the CLIMACS simulations), ran for 500 years, and were replicated for 20 plots. Two climate change scenarios were used, those generated from the OSU GCM (Schlesinger and Zhao 1988) and GISS (Hansen et al. 1983). The sensitivity of forest dynamics at Mount Rainier, WA (46.8° N, 121.7° W, 1654m) and Gold Beach, OR (42.4° N, 124.4° W) to climate change was also tested, using the species parameters set for 44° N. These results must be viewed as more tenuous than the results for the Andrews, because of differences in species characteristics at these two different latitudes.

ZELIG was also used to begin studying 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 ending at specific 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 corresponds to the OSU 2xCO₂ equilibrium scenario, and the 1300 GDD increase corresponds to the GISS 2xCO₂ equilibrium scenario.

Carbon Model Results

Potential changes in carbon storage in the central Oregon Cascades was 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 simple 5° C warming scenario was applied at three elevations in the Oregon Cascades (Urban et al. 1990).

RESULTS

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 5-8). Generally, the Holdridge model does a good job of separating forest from non-forested land. The main forest types in the Holdridge model under current conditions are temperate forest and boreal forest, whereas the SAF classification has eight major forest types delineated based on the dominant tree (e.g. Douglas-fir forests). All the forests west of the Cascade crest are considered 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. The Holdridge estimate of forested land in the region reasonably approximates the Forest Service estimates of forested land (Holdridge 318,000 km² vs. 290,000 km² USDA 1989).

Estimated Vegetation Change

Major shifts in vegetation patterns occur in the Northwest under four climate change scenarios, according to the Holdridge system (Smith et al. submitted). Overall, 26% (OSU) to 90% (UKMO) of the tri-state region will change from one Holdridge vegetation class to another (Table 5, Figures 5-8). Most vegetation change is predicted under the UKMO climate scenario, with least change predicted under the OSU scenario. Total forested area decreases under all scenarios from 5 to 25%. Boreal (subalpine) forests decrease by at least 50%, while temperate forests generally contract (except for the OSU scenario in which these forests increase by 20%). Temperate forests remain or expand at higher elevations in the region. In contrast, warm temperate forest expand many fold.

Interpreting what these changes in broad vegetation classes means in terms of more specific forest types identified in the introduction 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 in the middle of the eastern United States (Holdridge 1967, Kuchler 1964). Thus it appears that the Douglas-fir - hemlock forests decrease in regional extent, being replaced by more drought tolerant oaks.

Assumptions/Limitations

The limitations of this analysis are numerous and should be kept in mind when analyzing the output. First, the climate change analysis assumes that the Holdridge system adequately defines current vegetation patterns in the region, and that current climate-vegetation correlations are unchanged in the future. Although the Holdridge system only correctly classifies 40% of the globe's vegetation, the model does a reasonable job of separating forest and non-forest vegetation in the Northwest. It is uncertain whether current climate-vegetation correlations will remain unchanged in the future. New broad-scale vegetation models are being developed (Neilson et al. in press, Prentice) which are based on a mechanistic understanding of how climate controls vegetation patterns. These models should be more robust under different climates. All vegetation models used in climate change analysis should be extensively tested, either in different parts of the world, or at different times in the past (e.g. last 15,000 years).

The model also does not simulate the dynamics of vegetation change. The climate change results must be viewed as a snapshot of future vegetation patterns after a double CO₂ climate change has occurred and the vegetation has come back into equilibrium with the regional climate. In other words, forest dynamics (tree establishment and migration) are not simulated by the model.

The model only simulates potential natural vegetation; land use is not considered in the model. The influence of soils on vegetation is not factored into the analysis, nor are the direct effects of higher CO₂ concentrations on plant growth. Finally, the life zone classifications are very broad and applied on a coarse resolution. Interpreting the vegetation change scenarios in terms of actual species distribution is problematic.

Local Climate-Forest Zone Correlations

Mean annual temperatures of major plant 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. in press). Thus, a 2° degree warming would completely shift a forest type one zone upward; a 4° degree warming would shift them two zones upward (Franklin et al. 1990).

The potential impact of climate change on the elevation and areal extent of forest zones in the central Oregon Cascades was estimated using current correlations between forest zones and mean annual temperature. Two simple climate warming scenarios (+2.5°C and +5°C) were used

to drive the correlational model (Franklin et al. in press). Douglas-fir dominated forests would increase from 8% of current forested land to 39 or 27% (Table 6, Figure 9). The moister western hemlock forests would decrease in areal extent. Subalpine and alpine forests would decrease in areal extent. Decreases in area of upper elevational forests is simply a function of less area occupying a given elevational band as elevation up a mountain range increases. Total forested area would decrease east and west of the Cascade crest (Table 6).

This correlational approach has the same limitations as those discussed for the Holdridge approach, except the taxonomic resolution is much finer. Also, the approach assumes that current forest zones will not change in composition, all the species in them will move an equivalent distance upslope. However, paleoecological data clearly indicate that this assumption is incorrect. Species moved independently in the past in response to warming after deglaciation (Davis 1981, Webb). 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

Before future simulations of forest composition as simulated by CLIMACS are discussed it is important to evaluate how well the model simulates current forest dynamics. CLIMACS 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 predicts 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 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 on the Oregon coast (Dale and Franklin 1989). Soil moisture status was not changed in the scenario. The warming scenario was imposed on a stand 140 years old. Under current climate conditions, the composition of the stand would change from one dominated by Douglas-fir to one dominated by western hemlock (Figure 10). 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 codominant (Figure 10).

Assumptions/Limitations

The limitations of gap models will be discussed fully after the ZELIG results are summarized. One limitation unique to the CLIMACS analysis ~~are~~^{is} that soil moisture was not

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altered so the drought effects of warming were not analyzed. These could be quite pronounced in the Northwest under the GFDL and UKMO scenarios.

Forest Gap Models - ZELIG Results

Simulations of Current Vegetation

Much of the work in adapting ZELIG to run in the Northwest was spent developing a list of species parameters (e.g. growing degree limits) for inclusion in the model (Urban et al. 1990). Climatic correlates with tree species range limits were established for a number of latitudinal bands in the Northwest, ranging from a species southern geographic limit to its northern limit. A complicating result of this analysis in terms of modeling forests throughout the Northwest is the fact that growing degree day (GDD) limits for a species vary with latitude. For some species, the maximum at higher latitudes is greater than the minimum at lower latitudes. There are several explanations for this, ranging from genetic variation within a species, to the possibility that some other factor (soil moisture, snow pack, wind) besides GDD limits species distributions in some parts of their range.

This 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. Either the local parameter suite, ^{and} or the regional limits are the two choices. In the ZELIG analysis, parameters for the latitude of the H.J. Andrews site were used in the model runs. For climate change analysis, this assumes that seed sources will be restricted to the area surrounding the site (within about 100 km).

Despite the problems the genetic variability of a species presents to modeling forest response to climate change, the variability will provide a species the ability to better respond to climate change. The probability of a genotype being present in a species adaptive to a future climate is increased with greater genetic variability within a species.

The results from the ZELIG simulations for current and future conditions at Gold Beach, OR, H.J. Andrews, OR, and Mount Rainier, WA are summarized in Figure 11. The model does a poor job of simulating current vegetation patterns at H.J. Andrews. At 500 m, Douglas-fir and western hemlock are the dominant trees in the current forests. In the model simulation, chinkapin and ponderosa pine are dominant. 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 the Andrews. The model performs better at 1000m, where Douglas-fir and western hemlock dominate natural stands and modeled stands. Douglas-fir is still underestimated by the model, however.

A priori one would expect the model not to perform as well at the two other sites because of the apparent latitudinal differences in species adaptations to climate. At Gold Beach (where

annual precipitation is greater than at the Andrews, and temperatures are 1.3° C warmer), current forests are dominated by western hemlock and Sitka spruce (Franklin and Dyrness 1988). At the end of the 500 year run, the model predicts chinkapin and tan oak as dominants. Hemlock is a very minor component (sitka spruce was inadvertently left out of the species set, will be rerun but won't change outcome). Again the model is biased towards predicting a drier type of vegetation (even more so than at Andrews) than what actually occurs at the site.

At 1600m elevation at Mount Rainier, mountain hemlock and silver fir are dominant with subalpine fir present (Franklin and Dyrness 1988, Franklin et al. 1988). Silver fir, mountain hemlock, western white pine, subalpine fir are simulated as dominant species by the model. In terms of the dominant trees, the model does a good job (better than at the other two sites) of simulating the forest stand composition. In sum, ZELIG appears to be biased towards simulating drier types of vegetation at warm sites, but does a better job of forest simulations at higher sites. It does not simulate the dynamics of Douglas-fir well (Hansen et al. unpublished).

Estimated Changes in Forest Composition

ZELIG predicts major changes in species composition under the OSU and GISS climate scenarios (Figure 11). Under the OSU scenario, the dominant trees simulated under current conditions are replaced by tanoak and red alder at Andrews. At Gold Beach, dominants under current conditions are replaced by red alder. At Rainier, vegetation change is less, with the major change being a replacement of mountain hemlock with western hemlock. The driving factor behind these 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 that of the predicted climate. At Gold Beach, only red alder and tanoak will grow.

The increase in temperature under the GISS scenario is so great that GDD limits at 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. In essence the model predicts an upward movement of species distribution in the Washington Cascades.

The general response of mid-elevation forests at Andrews to the transient climate scenario varies with the age at which the warming applied (Urban et al. 1990). If the warming is applied at a stand age of 200 or 500 years, a short episode of high tree mortality occurs and the total biomass on the plot decreases. The total stand biomass doesn't return to prewarming levels because of the growing degree constraints on tree growth as discussed above. If the warming began from the beginning of the simulations, succession to more heat tolerant species proceeds without significant forest dieback.

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 their current distribution reflects their environmental tolerance, and that the species grow best at the center of its range (Urban et al. 1990). Temperature (through growing degree day totals) is assumed to be the primary control of species range limits. Genetic variability with a species parameter set is assumed to be non-existent. Seeds of all the species included in the simulation are assumed to be instantaneously available if the climate is favorable for their germination. Other assumptions are discussed by Urban et al. (1991). The form of the species response functions to climate is assumed to be correct and similar for all species.

The limitations of Northwest forest stand models are substantial at this point in their development. The ZELIG model has problems simulating low elevation (warm) forests in the Northwest, and consequently the 2xCO₂ scenarios can only be interpreted in terms of relative change in dominance. Specific changes in species dominance are likely inaccurate, except perhaps for the Rainier site. Thus problems probably exist both in the species parameterization and form of the model algorithms.

More importantly, the models do 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). Moreover, the simulation of soil moisture is biased towards simulating wetter conditions than what actually occurs at a site, because vegetation cover does not affect available soil moisture in the model. Also the contribution of snowmelt to soil moisture during the spring and early summer in the growing season is underestimated. Finally, other factors besides temperature and soil moisture may limit species distributions in particular regions, such as chilling requirements along the coast (Leverenz and Lev 1987) and snowpack at higher elevations (Scott 1980).

The model simulations do not consider the direct effects of enhanced CO₂ concentrations on water use efficiency or changes in disturbance frequencies (Urban et al. 1991). Model output also depends in part on the species assemblages input as potential occupants of a stand. Many of the species specific parameters are expressed relative to the other species in the assemblage. These could change as assemblages change, they remain constant in these model runs.

Potential Changes in Carbon Storage

A climate warming of 5° C could decrease detrital carbon stores by 30% across a diverse

array of sites (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. Production would have to increase by about 10% to offset these losses. The increase in production is unlikely except at middle elevations. Low elevations could be constrained by low soil moisture and replacement of Douglas-fir by slower growing species. Shallower soils at higher elevation may limit production increases there. 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. (in press) suggests that there could be a net loss of 60 Mg carbon per hectare from the Oregon Cascades.

It should be emphasized that this analysis does not factor in changes in species composition, nor the potential for catastrophic forest dieback (Neilson personal communication) to inject a pulse of carbon into the atmosphere. Predicted changes to less-productive forests adapted to warmer and drier conditions could substantially reduce the amount of carbon stored in the Northwest.

To put the potential carbon loss in perspective to recent land use changes, conversion of old growth forests to younger plantations in western Oregon and Washington has resulted 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 as yet not quantitatively modeled in the Northwest, the effects of climate change on forest composition and structure could be felt initially and most extensively through altered disturbance regimes (Overpeck et al. 1990, Franklin et al. in press). Disturbances destroy the resilience of the existing forests and coupled with climate change provide conditions for forest reestablishment that may be more severe than previously existed. As noted by Brubaker (1986) "[disturbances] should also mitigate the lagging effects of long tree lifespans by accelerating rates of population decline when climate change makes conditions unfavorable for seedling establishment."

Fire frequencies are likely to increase in the region given increased temperatures, unchanged precipitation and higher potential evapotranspiration. In southern Oregon increased fires could increase the dominance of some hardwood species that sprout after fires. (e.g. tanoak; Franklin et al. in press). The primary effect of fire would probably be one of speeding the conversion of a forest to one favored under warmer conditions.

New or more severe insect problems are probable given projected climate change. The altered climate may provide a more favorable environment for the insect or the trees may become more susceptible to the insect pest as a consequence of climate-change increases in tree stress. 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, 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 coastal and Cascade mountains rarely experience sufficient heat for the second generation to develop sufficiently to overwinter; hence, to 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 frequency and severity of pest outbreaks are likely in forest stands subjected to increased physiological stresses associated with climate change (Mattson and Haack, 1987). Even under conditions of stable climate, the majority of pest outbreaks are associated with increased host-plant stress (Franklin et al., 1991).

Disturbances can be viewed as events that hasten the adjustment of forest vegetation to the current climate conditions. But this could be disruptive as climate change may create more severe conditions for forest reestablishment which can cause significant changes in the forest composition and function (Franklin et al., 1991). Transitions in vegetation types will be a problem as forest loss may occur faster than forest reestablishment, especially at the lower and upper tree lines. There will likely be a shift in area from forest to non-forest vegetation (Franklin et al., 1991). "In general, natural forest ecosystems, with their greater compositional and functional redundancy, are expected to show greater resistance to change and recover more rapidly following disturbance than are intensively managed forests." (Franklin et al., 1991).

Major Uncertainties

Transient Dynamics

The model results presented here assume an instantaneous climate change, 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 assumption is the lack of transient climate change scenarios (two GISS transient scenarios are available however, Hansen et al. (1983)). Simulating transient climate change using atmospheric models is a difficult task, necessitating better ocean-atmosphere feedbacks. Incorporating a more realistic ocean circulation model in a climate model greatly increases the computer power required to operate the model, and taxes the fastest computers now available. Other technical and conceptual issues need to be resolved as well before transient scenarios can be produced.

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 still a ways off. Local scale models, such as forest gap models, are available for driving by a transient climate scenario. Several scenarios of the transient response of forests to climate change have produced in other parts of the U.S. (Urban et al. 1989, Botkin et al. 1989?). However, forest gap models in the Northwest still need refinement in their simulation of current forests before their simulations of future climate impacts can be considered to be more accurate.

Interestingly, the simple transient scenario used in the ZELIG approach suggests that biological inertia (e.g. the long lifespan of the forest trees in the Northwest) may not significantly delay changes in forest composition. The magnitude of the climate warming is so great that forest dieback occurs even in mature trees. This result is driven by the temperature limitations imposed on the species in the modeling runs which may not be relevant in lower elevational forests. Still, changes in soil moisture could be substantial enough that mature trees rapidly dieback to be replaced by more drought adapted species.

One difference between the eastern and western U.S. in terms of transient responses of vegetation is the differences in dispersal distances required for a species to track its favored climate. The generally flat terrain in the eastern U.S. means a 1° C temperature change will move a climate zone a considerable distance latitudinally. In the west, the mountainous terrain means that a 1° C change will move up only a few hundred meters of elevation and perhaps only a few km 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 elevational band above the highest elevation in the local region). Thus mountain vegetation will more likely stay in equilibrium with the changing climate than eastern forests.

Genetic variation in certain western tree species is relatively high (e.g. Douglas-fir). Thus, within a small region, the probability of a genotype being present that is adapted to a potential future climate is relatively high. However, current forest management techniques limiting the range of genotypes being replanted on cutover sites may decrease the ability of local *aged* forests to successfully adapt to future climate change.

Direct Effects of CO₂

The other major uncertainty in predicting forest response to climate change is the potential effect of higher CO₂ concentrations on forested ecosystems. Many assessments of the impacts of climate change on forests have focused on the potentially negative direct effects of increased temperature and drought on the trees, but have not considered the potential impacts of elevated CO₂ on forests.

There is a substantial body of literature that photosynthesis is increased and stomatal

conductance decreased by supra ambient levels of CO₂ (Ågren, et al., 1991; Hollinger, 1987; Surano et al., 1986). However, the magnitude of the changes, especially for mature trees is uncertain. Also it is largely unknown if the changes in photosynthesis and conductance will persist as the tree acclimatize to the elevated CO₂ or if the increases can be supported by current nutrient levels in the forest soils.

The extent to which possible nutrient limitations in forest soils will limit the direct effects of CO₂ on productivity is also unknown. In a review of a series of experiments of the response of seedlings and young trees to CO₂, Jarvis (1989) concluded that tree growth was stimulated by added CO₂ 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 CO₂ and that the effects of drought stress were largely mitigated by elevated CO₂ (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 CO₂ debate is how will vegetation over a landscape respond to higher CO₂ concentrations. The scientific problem is one of developing the techniques to extrapolate the experimental work to a forest stand. One approach is to use simulation models. Solomon and West () investigated the impact of greater water-use efficiency of forest population dynamics with a simulation model. They concluded that forest response to elevated CO₂ was dampened 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 possible drier climate.

In another simulation study of forest stand processes, Shugart (1984) found that the primary effect of elevated CO₂ 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 CO₂. "Although...simulation studies of possible responses of forests to enhanced levels of CO₂ are based on simple assumptions and formulations, the indications that population dynamics may override the consequences of CO₂ fertilization are interesting. The direct effects of CO₂ must therefore be considered within the larger scale consequences of population dynamics and responses of different species to CO₂-induced climate change" (Ågren et al., 1991).

CONCLUSIONS

Climate Induced Changes in Forest Composition and Distribution

Despite the uncertainties and concerns on model precision addressed above in the discussion of climate change impacts on Northwest forests, 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, given the GCM scenarios of warmer temperatures and generally unchanged precipitation and ignoring the potential mitigating effects of increased CO₂ concentrations. The Holdridge, Elevation-zone, 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 5 to 25%. 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 Douglas-fir dominated forests are likely to increase in areal extent, while the more productive hemlock forests will undergo significant contraction. Subalpine and alpine vegetation is likely to disappear.

The forest modeling work, although potentially more precise, is still in need of additional refinement. ZELIG results do show an upward movement of forest types and a general decrease in forest biomass. The model does not simulate low elevation or dry sites well. Upper elevation simulations perform better, perhaps because temperature actually does become the limiting constraint on 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 would speed the conversion of forest types and decrease the biological inertia represented by long-lived trees. Even without disturbance, the ZELIG results suggest that mature trees would dieback under the 2xCO₂ climate conditions simulated by GCMs.

Implications for Forest Management

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

- 1). Given current rotation lengths and the possibility of substantial climate change over the period of that rotation, what species should be planted now?
- 2). How much must current uncertainties in climate predictions and vegetation response be reduced before irreversible management practices predicated on climate change are implemented?

May 28, 1991 Draft - Do not quote or cite

3). Are their "no regrets" management practices for adapting to climate change that can be implemented 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 atmospheric concentrations of CO₂?

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ACKNOWLEDGEMENTS

Dean Urban from the University of Virginia and colleagues at the Pacific Northwest Lab of the U.S. Forest Service supplied the ZELIG model and the initial 2xCO₂ climate simulations through Interagency Agreement DW12934129. Charles Halpern of the Department of Forest Sciences at Oregon State University provided climate data for specific localities in western Oregon and Washington. Terry Droessler at the Environmental Research Laboratory, Corvallis, performed the 2xCO₂ simulations for Gold Beach and Rainier. The authors thank Don Phillips and Ron Neilson for reading an earlier version of the manuscript.

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Table 1a. Total forest land in the Pacific Northwest (USDA 1989). Data is for 1987.

State	Total Land Area	Total Forest Area	Timberland	Reserved Timberland	Other Forest Land
(thousands of acres)					
Idaho	52692	21818	14533	3051	4234
Oregon	61546	28057	22084	1777	4196
Washington	42483	21856	16848	2765	2244
Total	156721	71731	53465	7593	10674
		(290285 km ²)			

Table 1b. Timberland by ownership in the Pacific Northwest (USDA 1989). Data is for 1987.

State	All Ownerships	Total Public	Total Federal	Total State	Total Private	Total Forest Industry
(thousands of acres)						
Idaho	14534	11435	10310	1036	3099	1198
(percent)		79	90	6	21	39
OR	22085	13706	12462	827	8379	5114
(percent)		62	91	6	38	61
WA	16849	8652	5026	2025	8197	4588
(percent)		51	58	23	49	56
Total	53468	33934	27979	3903	19734	11000
(percent)		63	82	12	37	56

Table 2. Common tree species in the Pacific Northwest

<u>Abies amabilis</u>	Silver fir
<u>Abies procera</u>	Noble fir
<u>Abies lasiocarpa</u>	Subalpine fir
<u>Abies grandis</u>	Grand fir
<u>Acer macrophyllum</u>	Big leaf maple
<u>Alnus rubra</u>	Red alder
<u>Arbutus menziesii</u>	Pacific madrone
<u>Calocedrus decurrens</u>	Incense cedar
<u>Castanopsis chrysophylla</u>	Golden chinkapin
<u>Chamaecyparis nootkansis</u>	Port-Orford-Cedar
<u>Larix occidentalis</u>	Western larch
<u>Lithocarpus densiflorus</u>	Tanoak
<u>Picea sitchensis</u>	Sitka spruce
<u>Picea englemannia</u>	Englemann spruce
<u>Pinus monticola</u>	Western white pine
<u>Pinus lambertina</u>	Sugar pine
<u>Pinus ponderosa</u>	Ponderosa pine
<u>Pseudotsuga menziessii</u>	Douglas-fir
<u>Quercus chrysolepis</u>	Canyon live oak
<u>Quercus garryana</u>	Oregon white oak
<u>Thuja plicata</u>	Western red cedar
<u>Tsuga heterophylla</u>	Western hemlock
<u>Tsuga mertensiana</u>	Mountain hemlock

Table 3. The comparison of the impact of climate change on mean annual temperature and growing degree/days. The temperature is from historical records or calculated from the OSU and GISS GCMs while growing degree/days is calculated from the Weather routine in the ZELIG simulation model.

Location	Current Temp. C	OSU Temp. C	GISS Temp. C	Current Degree/Day	OSU Degree/Day	GISS Degree/Day
Forks, WA	9.7	12.0	14.7	1584	2367	3340
Rainier, WA	3.1	5.4	8.0	511	883	1360
Longview, WA	10.8	13.1	15.9	2007	2794	3774
Astoria, OR	10.4	12.7	15.4	1773	2595	3601
HJ Andrews, OR	10.3	12.6	15.3	1928	2645	3663
Crater Lake, OR	3.2	5.5	8.1	625	984	1458
Gold Beach, OR	11.6	13.9	16.7	2225	NA	4066
Ashland, OR	11.1	13.4	16.2	2191	2933	3882

Table 4. The comparison of the impacts of climate change on annual precipitation and potential evaporation (PET). The precipitation is from historical records or calculated from the OSU and GISS GCMs while PET is calculated from the Weather routine in the ZELIG simulation model (Urban 1990, Urban et al. 1990) using the Thornthwaite relationship. The ratios for precipitation and PET are GCM/Current condition.

Location	Current Prec. cm	OSU Ratio	GISS Ratio	Current PET cm	OSU Ratio	GISS Ratio
Forks, WA	302.3	1.45	1.27	62.8	1.10	1.21
Rainier, WA	289.3	1.45	1.27	42.5	1.16	1.34
Longview, WA	117.3	1.45	1.27	66.0	1.10	1.24
Astoria, OR	176.8	1.46	1.27	63.9	1.09	1.21
HJ Andrews, OR	135.9	1.46	1.27	64.0	1.10	1.24
Crater Lake, OR	469.8	1.46	1.27	41.4	1.18	1.34
Gold Beach, OR	210.0	1.47	1.26	65.4	1.09	1.22
Ashland, OR	48.0	1.46	1.26	67.0	1.12	1.27

Table 5. Areal extent of Holdridge life form classes before and after a double CO₂ climate change. Area (thousands of km²) and percent change (in parantheses) from current conditions are given for each life form catgory.

Life Form Category	Current Area	OSU	GISS	GFDL	UKMO
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 (Subapline) Forest	130	63 (-51)	26 (-80)	15 (-89)	0 (-100)
Temperate Forest	186	223 (20)	171 (-8)	142 (-24)	93 (-50)
Warm Temperate Forest	2	15 (571)	95 (4310)	78 (3521)	110 (4986)
Tropical Semi-Arid	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

Table 6. Percent of area in various vegetation zones in the central Oregon Cascade Range (latitude 44°30' north) under current climate and with increases of 2.5 and 5 degrees C (Franklin et al. in press).

Zone	Climate		
	Current	+ 2.5° C	+ 5.0° C
Western Slopes			
Nonforested	0	0	0
<u>Quercus</u> woodland	0	8	39
<u>Pseudotsuga</u>	8	39	27
<u>Tsuga heterophylla</u>	56	38	24
<u>Abies amabilis</u>	24	13	2
<u>Tsuga mertensiana</u>	9	2	0
Alpine	3	0	0
Total Forested	97	92	53
Cold Snow Zone ¹	24	9	1
Eastern Slopes			
<u>Artemisia</u> steppe	0	51	77
<u>Juniperus occidentalis</u>	29	14	11
<u>Pinus ponderosa</u>	22	12	7
<u>Abies grandis</u>	19	14	4
<u>Tsuga mertensiana</u>	17	6	1
Alpine	13	3	0
Total Forested	58	32	12
Cold Snow Zone ²	30	9	1

¹ includes half of Abies amabilis zone and all of the Tsuga mertensiana and Alpine zones.

² includes Tsuga mertensiana and Alpine zones.

Figure Captions

Fig. 1. Forest types in the Pacific Northwest (USDA 1970).

Fig. 2. Current and predicted mean monthly temperatures for three sites in the Northwest

Fig. 3. Current and predicted mean monthly precipitation for three sites in the Northwest

Fig. 4. Holdridge life-zone classification system (Holdridge 1967).

Fig. 5. Vegetation redistribution in the Pacific Northwest under the OSU climate scenario using the Holdridge life-zone classification systems (Smith et al. submitted). In the map on the lower right, red depicts the pixels that change from one vegetation type to another.

Fig. 6. Vegetation redistribution in the Pacific Northwest under the GISS climate scenario using the Holdridge life-zone classification systems (Smith et al. submitted). In the map on the lower right, red depicts the pixels that change from one vegetation type to another.

Fig. 7. Vegetation redistribution in the Pacific Northwest under the GFDL climate scenario using the Holdridge life-zone classification systems (Smith et al. submitted). In the map on the lower right, red depicts the pixels that change from one vegetation type to another.

Fig. 8. Vegetation redistribution in the Pacific Northwest under the UKMO climate scenario using the Holdridge life-zone classification systems (Smith et al. submitted). In the map on the lower right, red depicts the pixels that change from one vegetation type to another.

Figure 9. Potential shifts in forest zones under two different climate warming scenarios (Franklin et al. in press).

Figure 10. A. Simulations of current forests at Cascade Head using CLIMACS. B. Potential changes in forest vegetation at Cascade Head as simulated by the CLIMACS model (Dale and Franklin 1989). In both simulations, the model was initiated at year 140 using the stand structure of plots at Cascade Head was used to initiate the model at year 140.

Figure 11. Potential changes in forest tree species abundance at Rainier, WA, H.J. Andrews, OR, and Gold Beach, OR as simulated by ZELIG (Urban 1990, Urban et al. 1990, 1991). ABAM = *Abies amabilis*, ALRU = *Alnus rubra*, LTDE = *Lithocarpus densiflora*, PSME = *Pseudotsuga menziesii*, ABGR = *Abies grandis*, CACH = *Castanopsis chrysophylla*, THPL = *Thuja plicata*, ABLA = *Abies lasiocarpa*, CHNO = *Chamaecyparis nootkatensis*, PIMO = *Pinus monticola*, TSHE = *Tsuga heterophylla*, ABPR = *Abies procera*, LBDE = *Libocedrus decurrens*, PIPO = *Pinus ponderosa*, TSME = *Tsuga mertensiana*.

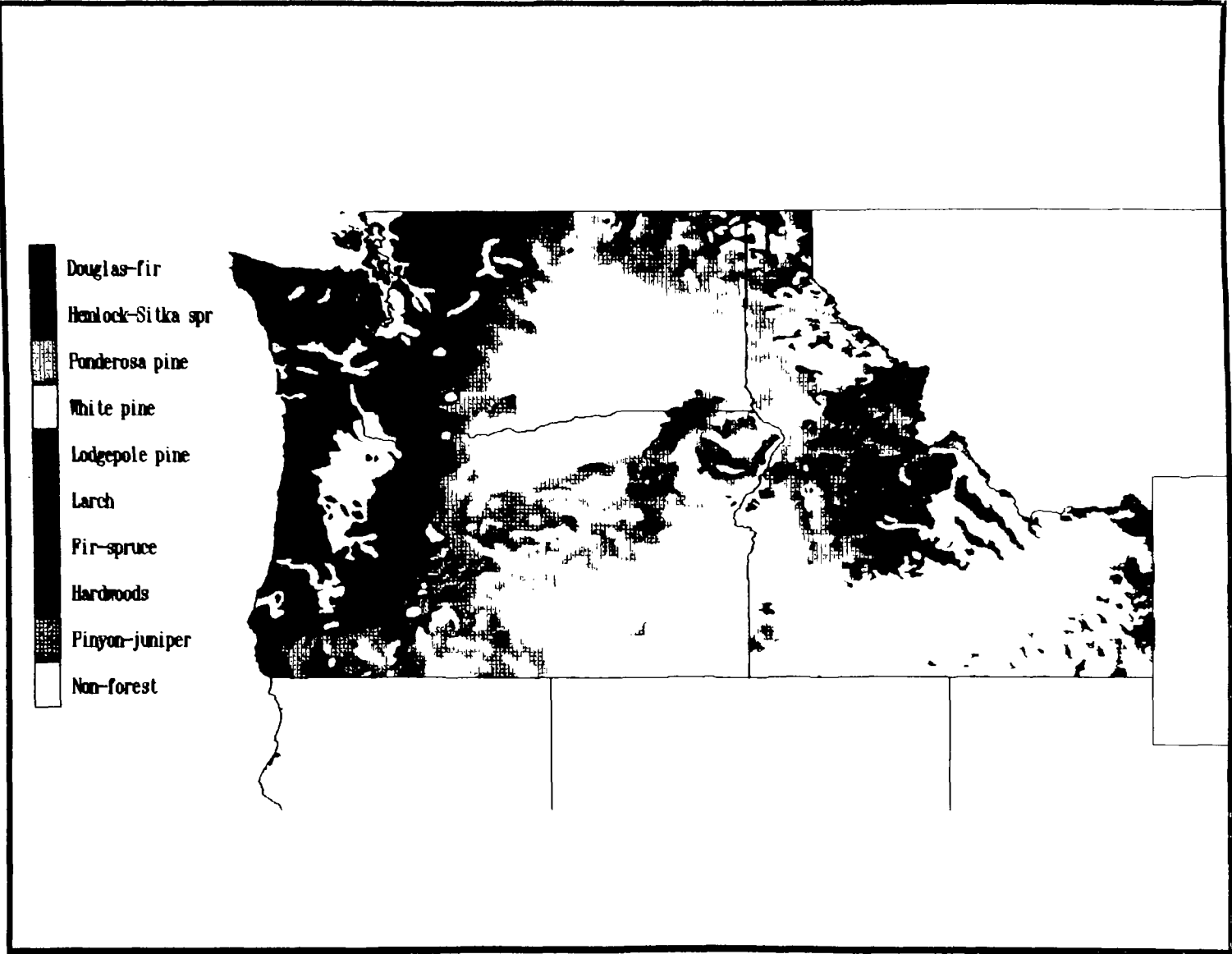
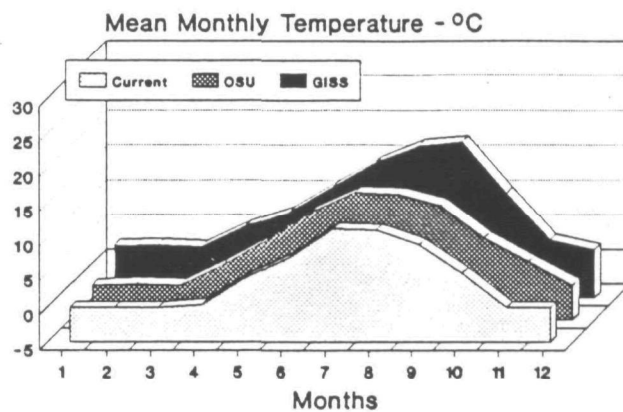


FIGURE 1

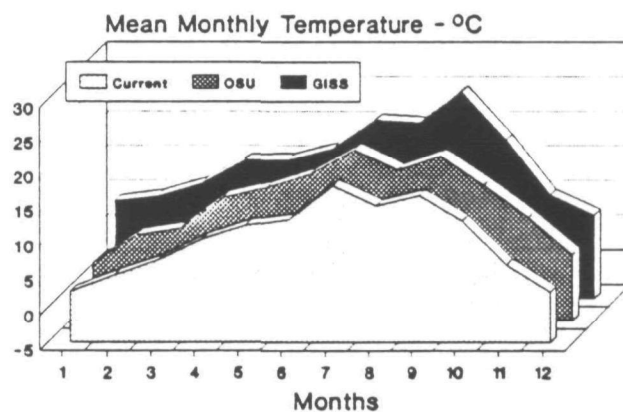
Rainier/Paradise, WA

Lat. 46.8, Lon. 121.7, Elev. 1654m



H.J. Andrews Forest, OR

Lat. 44.2, Lon. 122.2, Elev. 500m



Gold Beach, OR

Lat. 42.4, Lon. 124.4, Elev. 15m

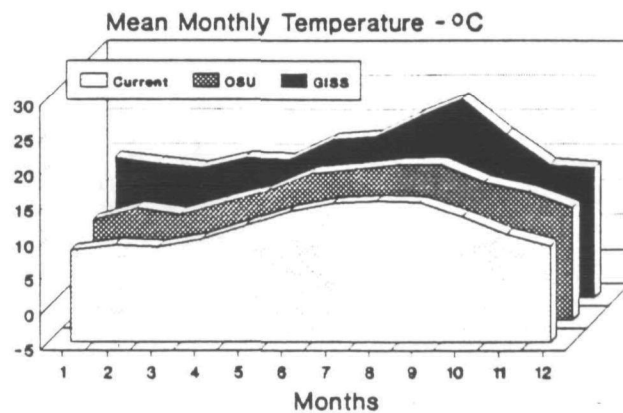
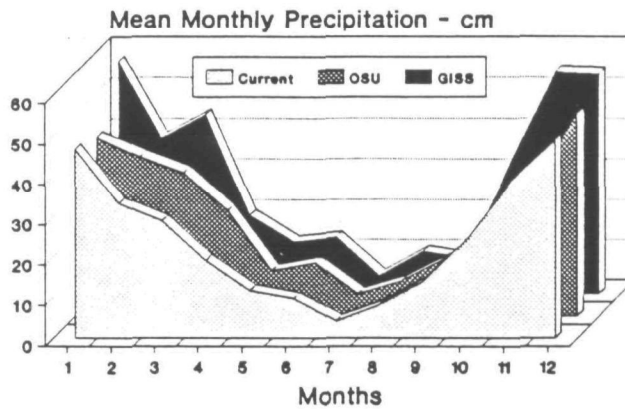


Figure 2

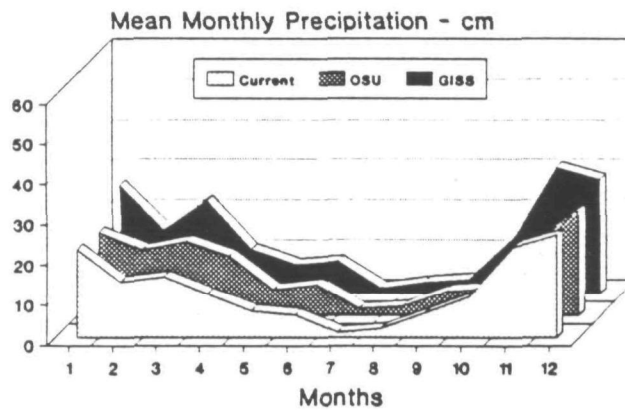
Rainier/Paradise, WA

Lat. 46.78, Lon. 121.73, Elev. 1654m



H.J. Andrews Forest, OR

Lat. 44.2, Lon. 122.2, Elev. 500m



Gold Beach, OR

Lat. 42.4, Lon. 124.4, Elev. 15m

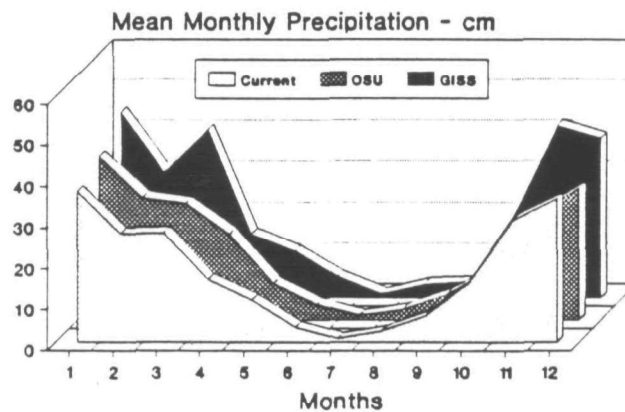


Figure 3

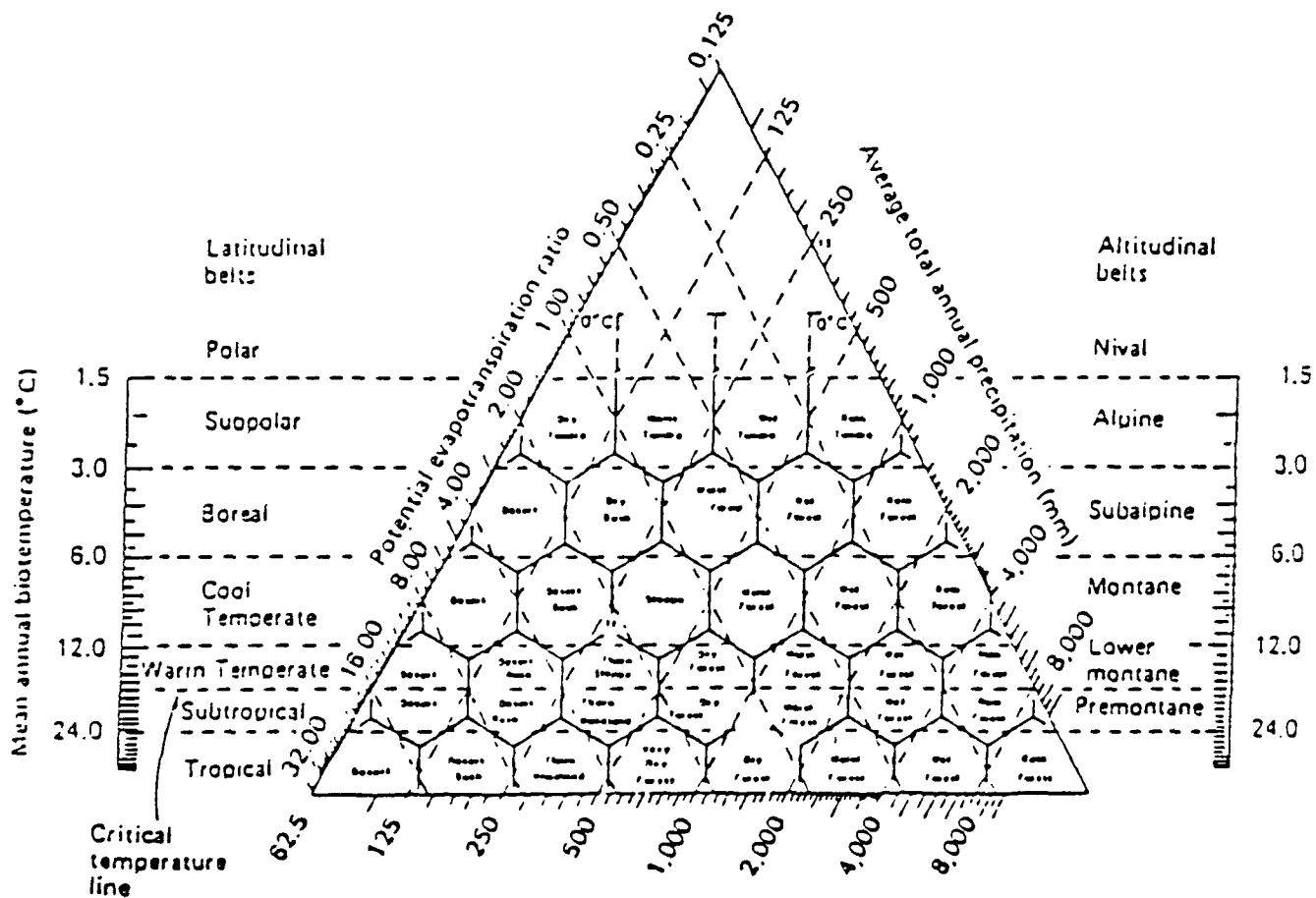


FIGURE 4

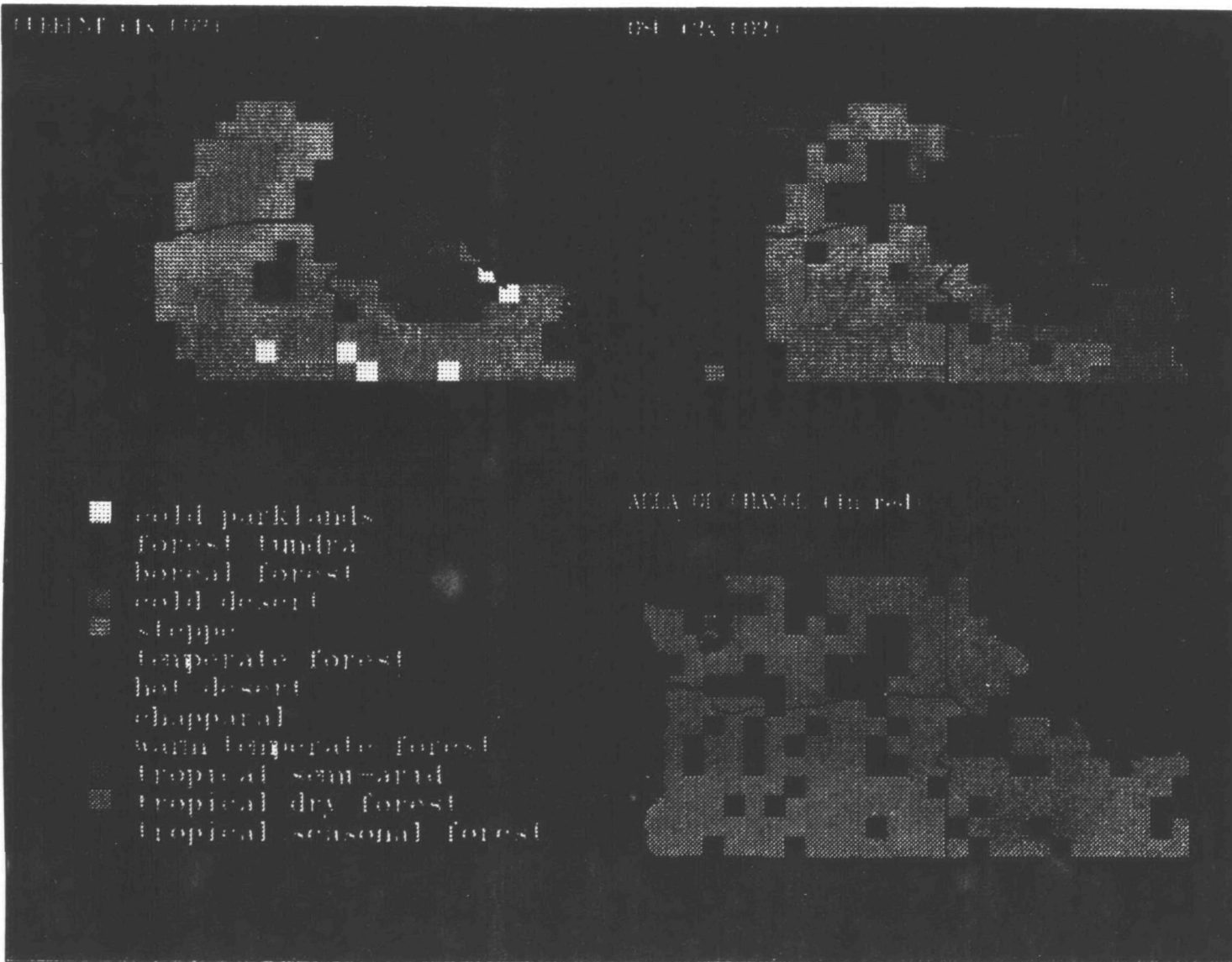


FIGURE 5

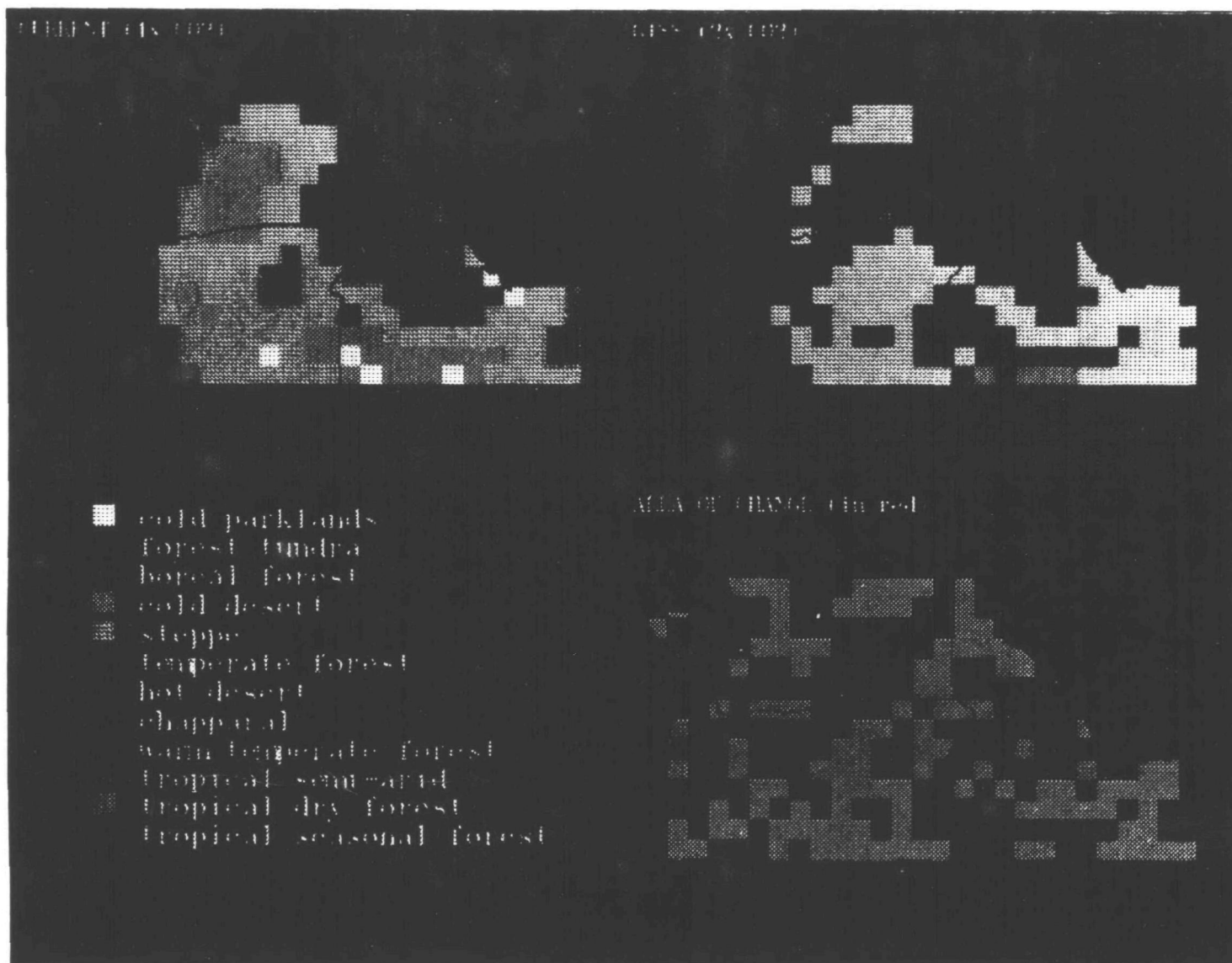


FIGURE 6

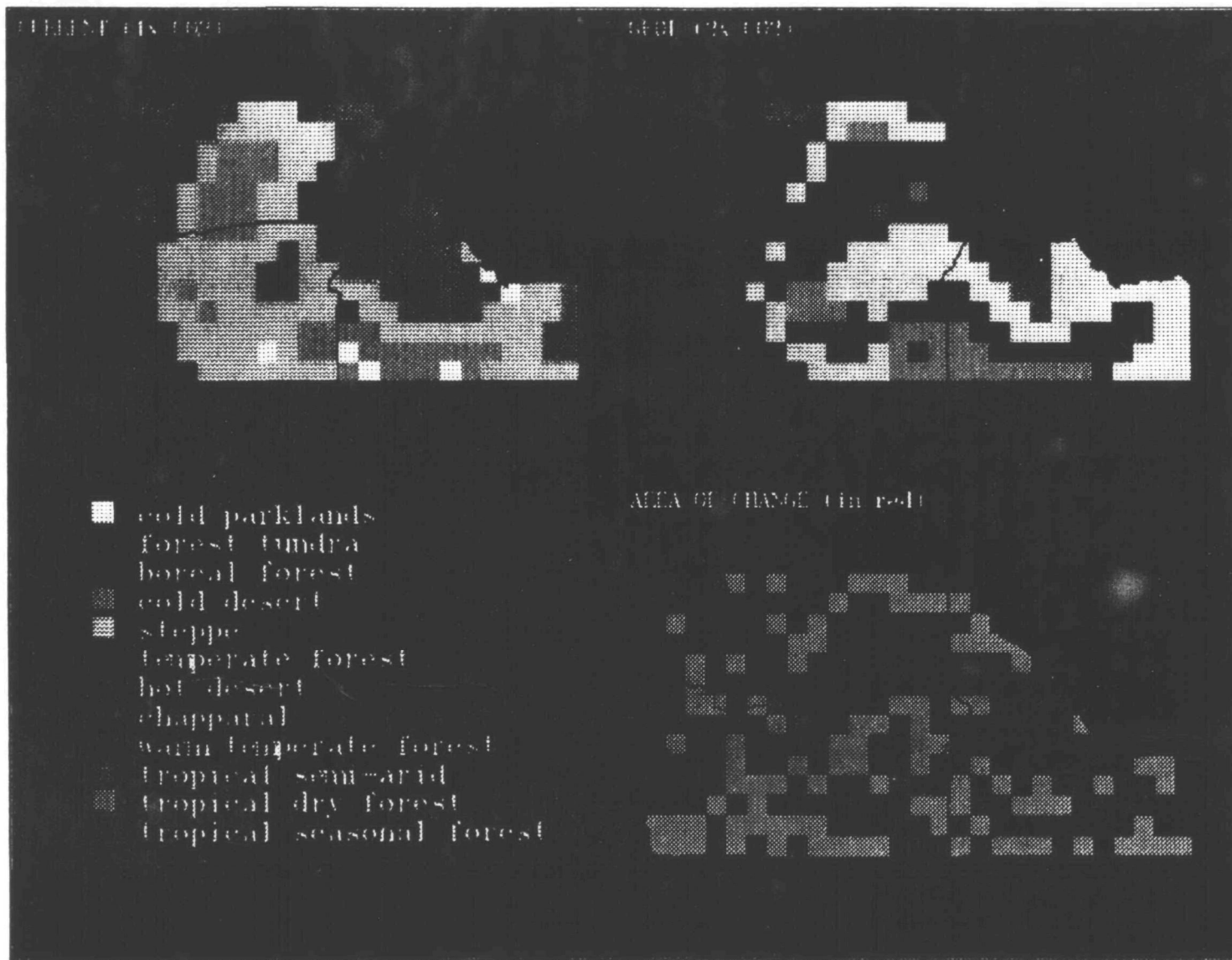


FIGURE 7

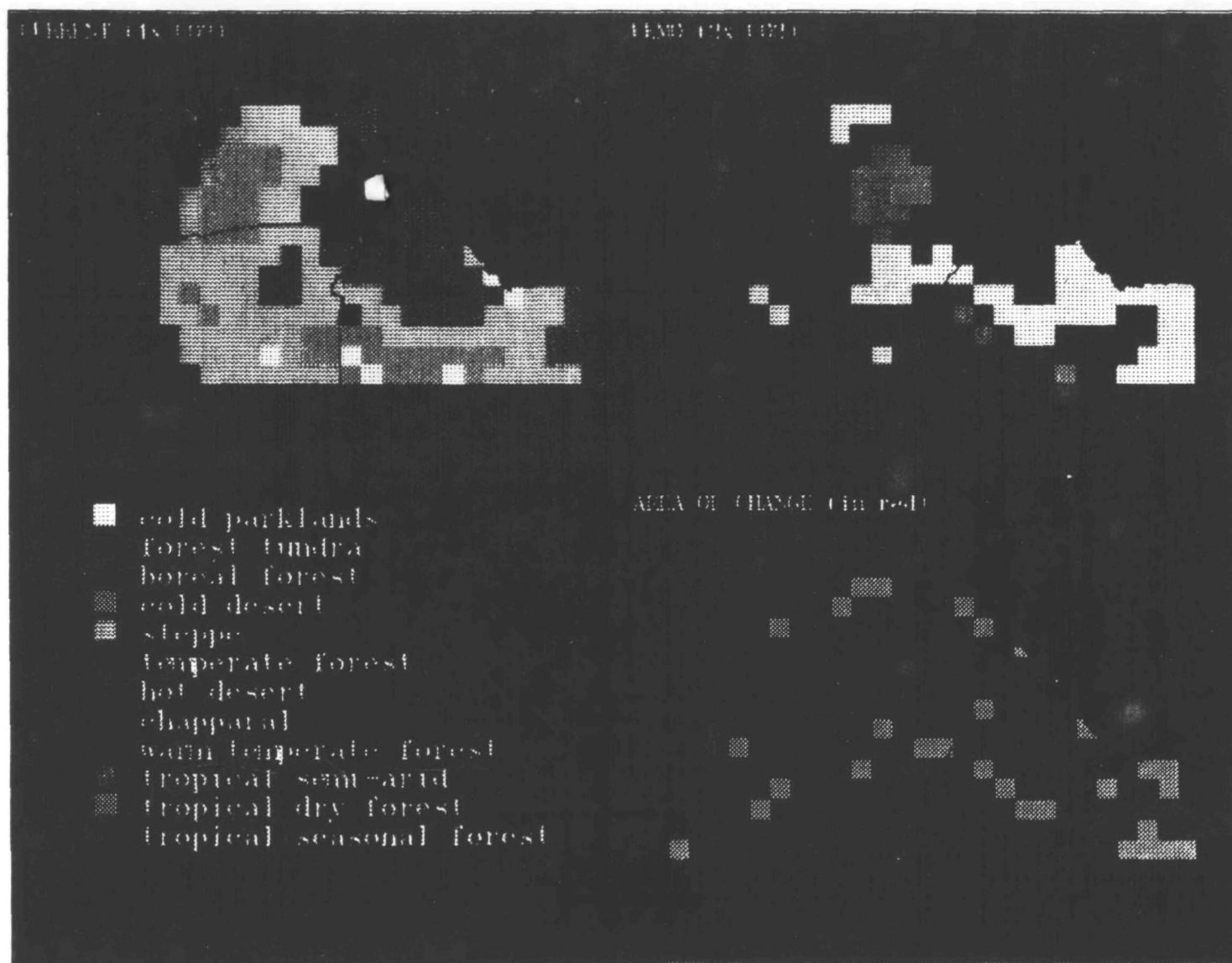
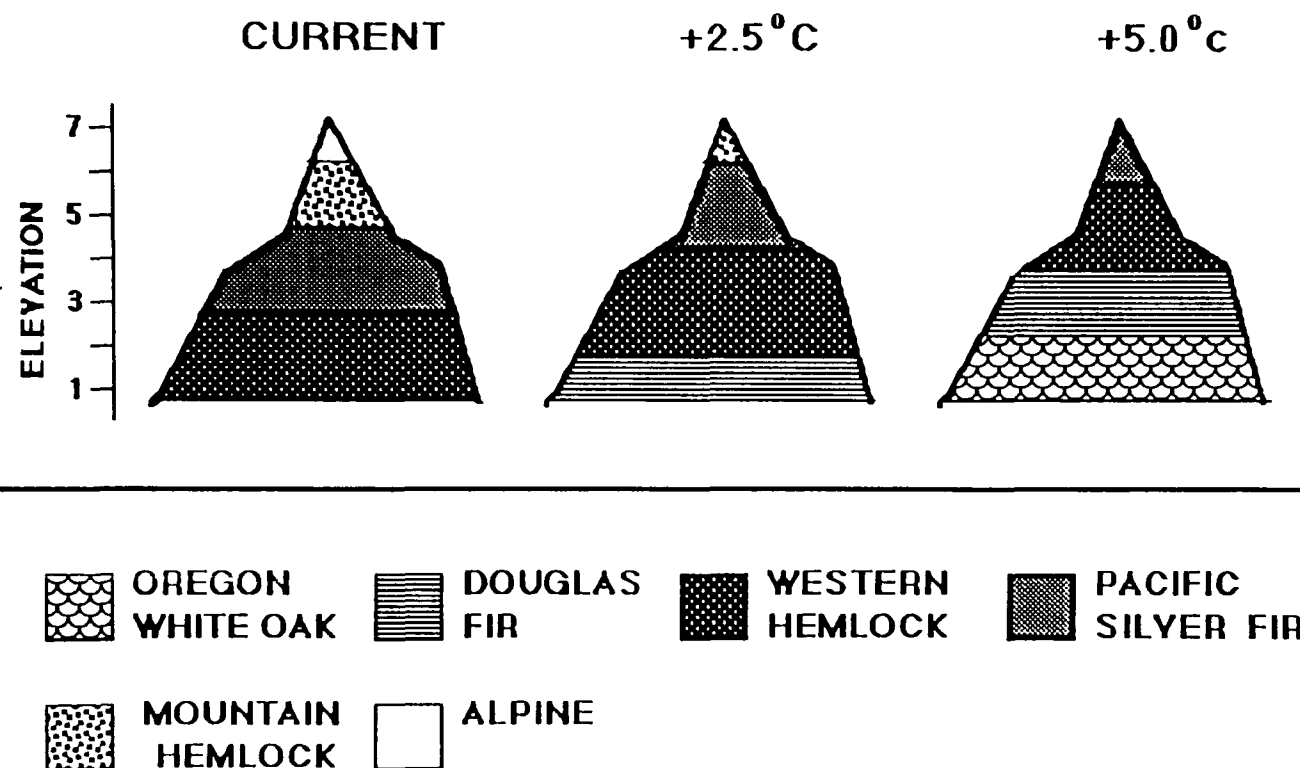


FIGURE 8

POTENTIAL VEGETATION CHANGE IN THE OREGON CASCADES



MANTECH / ERL-C

FIGURE 9

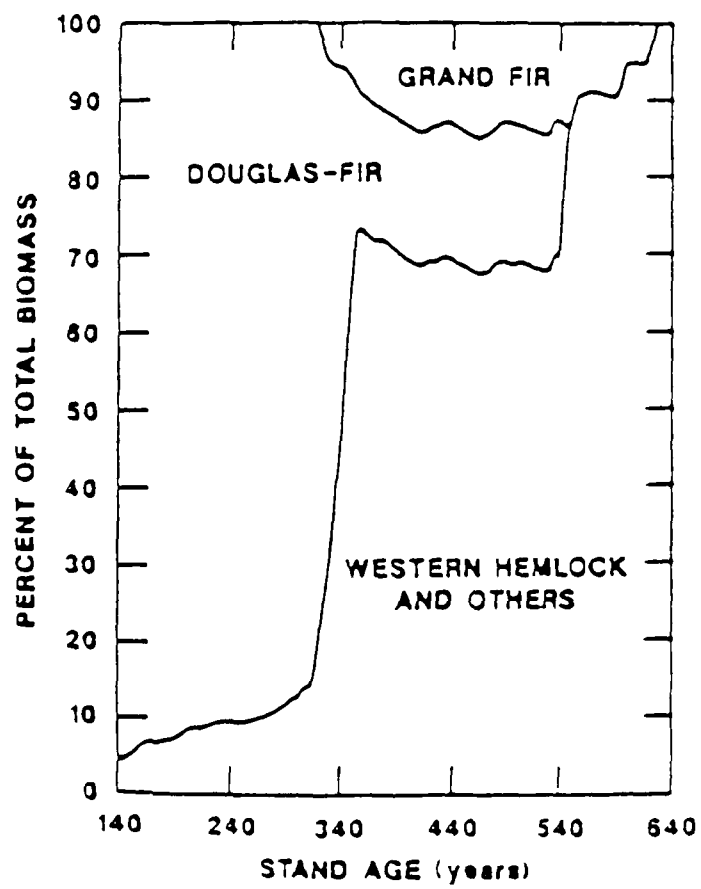
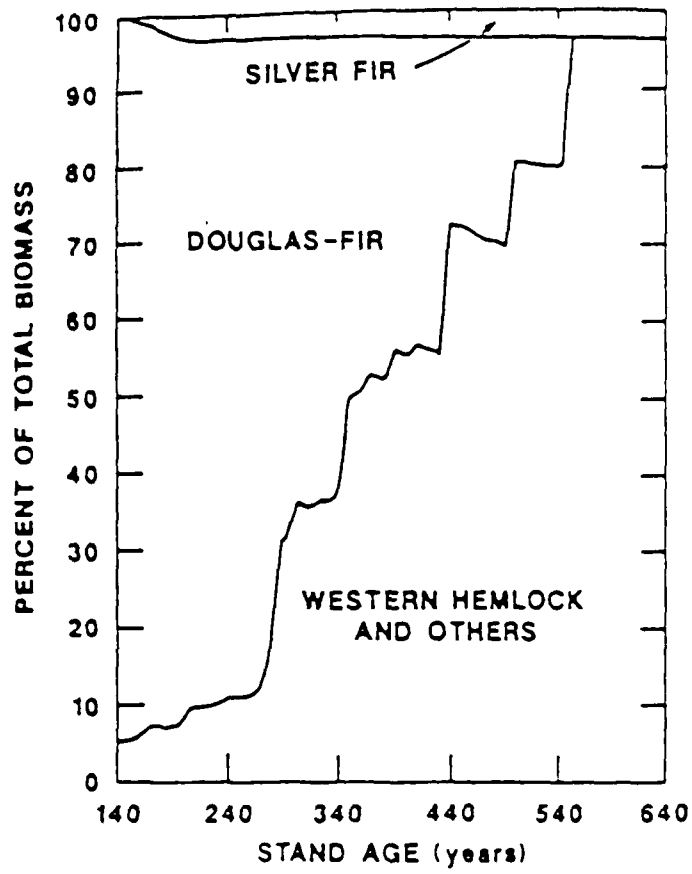


FIGURE 10 A & B

H.J. Andrews, Gold Beach & Mt. Rainier Species Relative Importance (%), Year 500

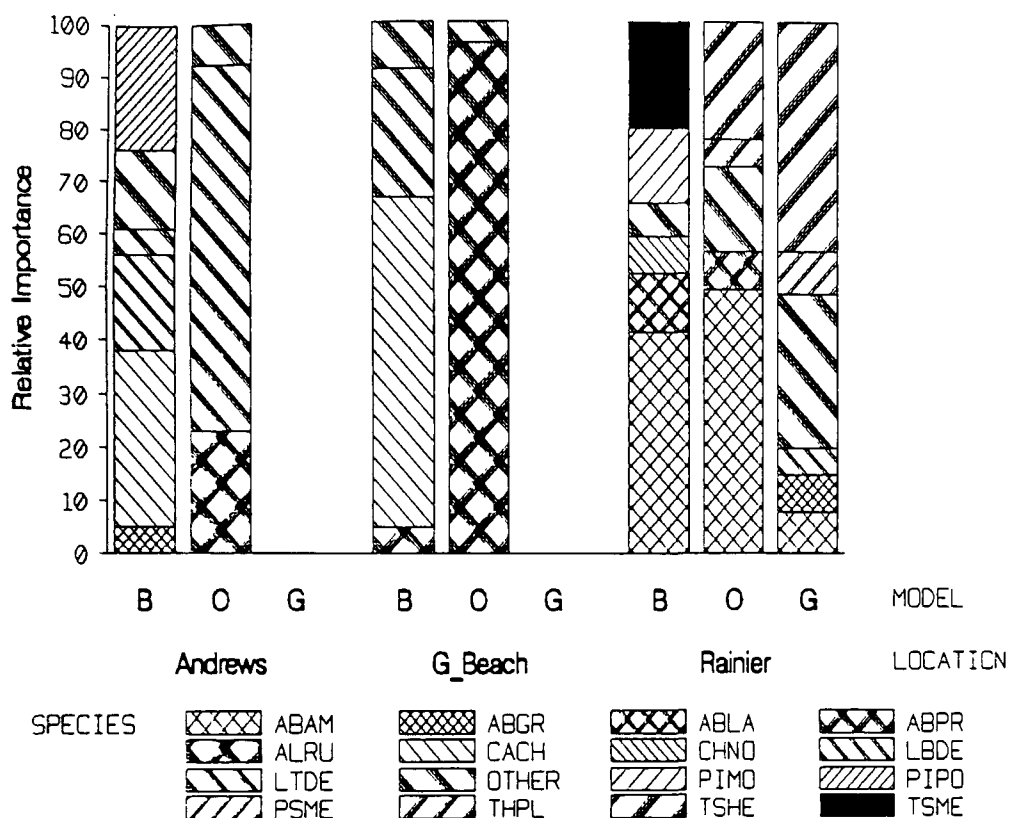


FIGURE 11