

## CHAPTER NINETEEN

## Effects of Global Climatic Change on Forests in Northwestern North America

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"This is how it happens," the Dinosaur said.  
 "Drought, fire, hurricanes and floods. Throw in a  
 little radon, and the next thing you know, you're  
 extinct."

—Steve Palay in *The Oregonian*, Sept. 25, 1988

## I INTRODUCTION

Dense coniferous forests characterize the Pacific Coast of northwestern North America. Such species as Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), and Pacific silver fir (*Abies amabilis*) are dominant trees. Both the species and the forest stands are noted for their potential longevity and productivity (Franklin and Dyrness 1973, Franklin 1988). The natural forests in this region have, on average, the largest organic matter accumulations per unit area of any major plant formation in the world (Franklin and Waring 1981).

It has been suggested that the humid temperate climatic regime of the Pacific Northwest buffers the forests against global climatic change (e.g., Woodman 1987). In fact, northwestern forests are probably quite vulnerable to major climatic shifts. This is because the most important environmental variable affecting the composition and function of these forests is the effective moisture regime (a product of temperature and precipitation) during the relatively dry summers (e.g., Waring and Franklin 1979, Zobel et al. 1976). Differences in moisture regime produce dramatic local and regional gradients in the species composition and ecosystem functioning (e.g., rates of productivity and nutrient cycling) of these forests. Locally this is evidenced in sharp differences between slopes having different aspects. Regional gradients, from coastal Sitka spruce (*Picea sitchensis*) to interior ponderosa pine (*Pinus ponderosa*) forests, are also related primarily to moisture regime (e.g., Grier and Running 1977, Gholz 1982). These climatic considerations suggest great potential sensitivity to global climate change in northwestern forests. The most important catastrophic forest disturbances on the Pacific Coast—wildfire and windstorm—are also climatically driven.

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indicating significant additional mechanisms for indirect influences of global climate change (e.g., Hemstrom and Franklin 1982, Agee and Flewelling 1983, Henderson and Peter 1981).

This chapter explores the potential effects of some proposed changes in global climate on the coniferous forests of the Pacific Northwest. We have accepted the scenarios for global climatic change provided by several existing global circulation models (Hansen et al. 1988) as the basis for our exercise; the uncertainties associated with these models are discussed in chapter 4. We consider vegetational shifts along local and regional environmental gradients, output from forest successional simulators, paleobotanical data on change during the Holocene, and effects of altered disturbance regimes. Benefits of increased atmospheric CO<sub>2</sub> receive limited consideration in our analysis but are discussed in chapter 8. Our objective is a collective judgment about probable effects of the global climatic change scenarios on forest ecosystems in northwestern North America and their implications for management of both commodity and preserved lands.

We propose that altered disturbance regimes, including intensities and frequencies of wildfires, storms, and outbreaks of pests and pathogens, will produce much more rapid changes in forest conditions than the direct effects of increased temperature and moisture stress (fig. 19.1). Hence, the potential indirect effects of climate change on biotic change should receive more attention from physical and biological scientists. Forest management can either exacerbate or reduce the effects of climate change on the productivity and biological diversity of northwestern forestscapes.

## II. PERSPECTIVES ON THE PROJECTED CLIMATIC CHANGES

Forest environments in the Pacific Northwest will become significantly warmer and drier under the three global climate change scenarios provided (Hansen et al. 1988). These

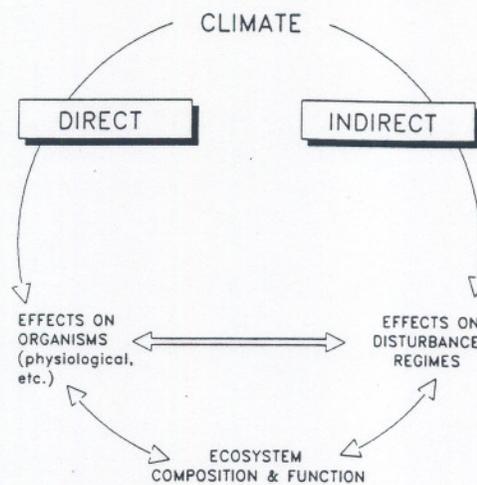


Figure 19.1. Climatic changes have both direct and indirect effects on ecosystem composition and structure.

models are consistent in projecting an increase in northwestern North America of 2°–5°C in mean temperature (both winter and summer) and little (–1 mm/day summer) or no change in precipitation. There are no seasonal shifts, so the pattern of relatively dry summers and mild, wet winters will persist.

Available moisture for plant growth will, of course, decline as the temperature increases, with no corresponding change in precipitation (table 19.1). Currently, northwestern forests grow under a wide range of temperature and moisture regimes; the range in mean annual temperatures in this forest region is about 5°C, and precipitation varies by an order of magnitude (approximately 3000 mm). The overall effect of warming without increased precipitation in this region will be increased potential evapotranspiration. A 5°C increase at Hoh River, Washington, for example, increases potential evapotranspiration from 537 mm/year to 881 mm/year. That temperature increase would also increase the number of months that potential evapotranspiration exceeds precipitation from 1 to 3 months at Hoh River, Washington, and from 6 to 8 months at Medford. Changes in actual evapotranspiration would depend on soil moisture storage; however, assuming that

Table 19.1. Hypothetical changes in evapotranspiration for three weather stations within forest zones of the Pacific Northwest, assuming an increase in temperature and no change in precipitation. PET, potential evapotranspiration (Mather 1974). AET, actual evapotranspiration (Mather 1974) with soil storage of 150 mm.

Station	Hoh River, Washington	H. J. Andrews, Oregon	Medford, Oregon
Vegetation Type	Spruce-hemlock	Hemlock	Mixed Conifer-Oak Savanna
Temperature (°C)	8.9	8.5	12.1
Precipitation (mm)	3492	2302	481
Current			
PET (mm)	537	547	822
AET (mm)	524	530	354
2.5°C increase			
PET (mm)	708	720	997
AET (mm)	675	687	408
5.0°C increase			
PET (mm)	881	895	1174
AET (mm)	818	840	448

such storage is constant between sites, we can conclude that changes in actual evapotranspiration are most likely to be greatest at wetter sites, such as Hoh River and H. J. Andrews (table 19.1).

Obviously, the climate change scenarios represent a massive climatic shift. For example, they can be viewed as equivalent to moving current climatic conditions at the base of a mountain upward between 500 m and over 1000 m in elevation; this is based on calculated lapse rates of about 4.8°C per 1000 m in southwestern Oregon and 4.0°C at Mount Rainier, Washington (Greene and Klopsch 1985). The climatic change is also equivalent to shifting current climates 200–500 km north of their current locations, that is, moving the climate of northern California into northern Oregon.

A simple assessment of an environmental shift of this magnitude can be made by relating it to forest community gradients or classifications for the Pacific Northwest (Franklin 1988), even though forest communities will probably not shift as intact multispecies units. Major plant series or vegetation zones differ by 1.5°–2.0°C in mean annual temperature at Mount Rainier, Washington (Franklin et al. 1988), and by about 2.5°C in southwestern

Oregon (Atzet and Wheeler 1984); hence, a 4°C temperature increase could shift a given forest site by as much as two vegetation zones. Sites currently occupied by communities typical of the mountain hemlock (*Tsuga mertensiana*) zone could be replaced by communities characteristic of the western hemlock zone (fig. 19.2). In southwestern Oregon some sites currently occupied by vegetation assignable to the white fir (*Abies concolor*) series could be replaced with vegetation representative of the ponderosa pine (*Pinus ponderosa*) series while other forested sites would shift to nonforested (e.g., chaparral) ecosystems.

Elevational shifts of this magnitude will, of course, produce massive changes in the proportion of regional landscape occupied by different vegetation types (fig. 19.2, table 19.2). For example, on the western slopes of the central Oregon Cascade Range the proportion of the landscape characterized by dry coniferous forest (area of Douglas fir series) would increase from 8% to 39% or 27% depending on the temperature increase; the area occupied by the productive and commercially valuable western hemlock series would, on the other hand, decline from 56% to 38% or 24% of the landscape. Loss of forested area to juniper savanna and sagebrush

steppe would predictably be massive on the eastern slopes of the central Oregon Cascade Range—a decline from 58% of the current landscape to 12% under the 5°C temperature increase.

Paleobotanical evidence suggests that vegetative shifts will be more complex and individualistic than simple shifts of intact vegetation communities and mosaics along environmental gradients. The simple projections provided here have assumed that intact forest communities (i.e., all species) will shift location as a unit as the environment changes. Recent studies strongly suggest that species shift independently, producing new combinations of plant species (Davis 1986, Delcourt and Delcourt 1987). For example, in the Pacific Northwest, dominance by Douglas fir is a phenomenon of the present inter-

glacial, but hemlocks and true firs (*Abies*) have been around for much longer periods (Tsukada 1982). Analyses based on physiological considerations also suggest varying responses by tree species to climatic change (e.g., Leverenz and Lev 1987).

Direct paleobotanical evidence of vegetative responses during the Holocene in the Pacific Northwest cannot be used to make precise projections of future vegetative change (e.g., Brubaker 1986, 1988). That is because every warming event causes complex and unique changes and because, in the case of the Pacific Northwest, paleobotanical studies are relatively few and confined mainly to lowland areas, especially the Puget Lowland and valleys of the Okanogan Highlands (Barnosky et al. 1987); almost no studies exist for major mountain regions. It is clear, however, that the projected changes will produce an environment hotter than any previously experienced during this interglacial. Mean regional temperature during the Holocene has varied by only about 5°C, and current temperatures were exceeded by a maximum of only 2°C during the early Holo-

Figure 19.2. Percent of area in major vegetation zones on the western and eastern slopes of the central Oregon Cascade Range (latitude 44°30' north) under current climate and with temperature increases of 2.5° and 5°C. Major shifts are predicted in elevational boundaries and the total area occupied by vegetation zones under global climatic change.

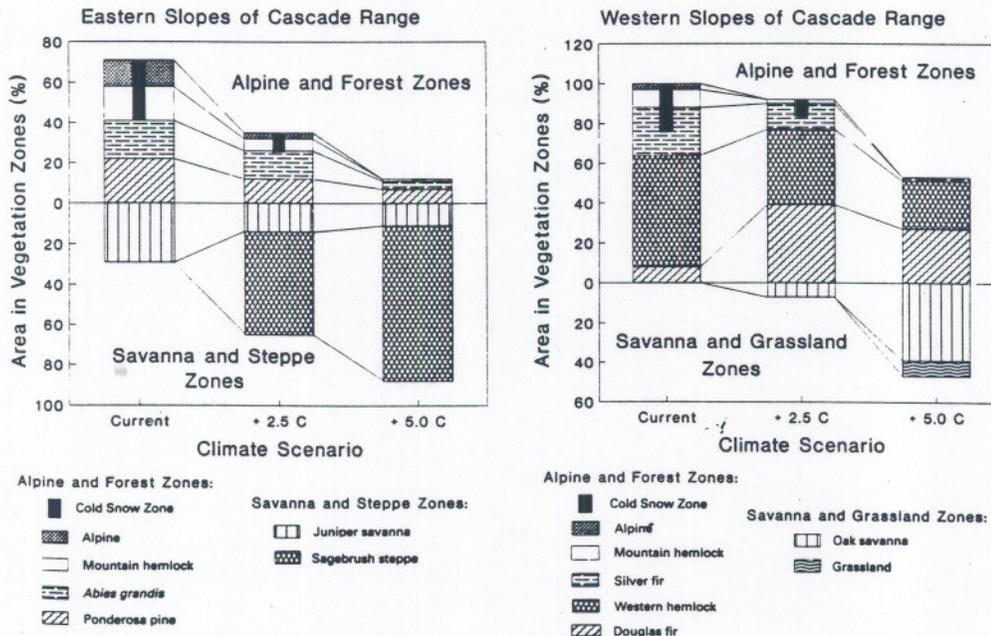


Table 19.2. Percent of area in various vegetation zones in the central Oregon Cascade Range (latitude 44°30' north) under current climate and with increases of 2.5° and 5°C.

Zone	Climate		
	Current	+2.5°C	+5.0°C
<b>Western slopes</b>			
Nonforested	0	0	8
Oak savanna	0	8	39
Douglas fir	8	39	27
Western hemlock	56	38	24
Silver fir	24	13	2
Mountain hemlock	9	2	0
Alpine	3	0	0
Total forested	97	92	53
Cold snow zone <sup>1</sup>	24	9	1
<b>Eastern slopes</b>			
Sagebrush steppe	0	51	77
Juniper	29	14	11
Ponderosa pine	22	12	7
Grand fir	19	14	4
Mountain hemlock	17	6	1
Alpine	13	3	0
Total forested	58	32	12
Cold snow zone <sup>2</sup>	30	9	1

<sup>1</sup>Includes half of silver fir zone and all of the mountain hemlock and alpine zones.

<sup>2</sup>Includes mountain hemlock and alpine zones.

cene, the period of maximum temperature during this interglacial (Brubaker 1988).

This section has focused primarily on community composition and structure. Shifts in the functional properties of the ecosystems, such as net primary productivity and decomposition and nutrient cycling, will be associated with the compositional changes. Functional shifts are important to consider, especially since they provide a feedback that can reduce or increase the effects of climate and changes in greenhouse-gas concentrations.

### III. EFFECTS ON ESTABLISHED FORESTS

We began our analysis by considering the effects of global change on established forests. An existing forest is expected to be more

tolerant of environmental changes than a forest that is reestablishing itself after a disturbance. The established forest is able to buffer the effects of altered conditions, such as increased temperature or decreased moisture, so they are felt only slowly. Tree seedlings attempting to establish themselves in a nonforested environment, such as after a wildfire or logging, are much more sensitive to current climatic conditions.

A model that simulates forest succession (CLIMACS) was used to examine effects of altered climates on forest composition and structure. This model is based on the JABOWA and FORET paradigm (Shugart 1984) but is adapted to ecological conditions in the Pacific Northwest (Dale and Hemstrom 1984). Fundamentally, it is a tree population model that tracks birth, growth, and death of indi-

vidual trees based on environmental conditions. Birth and death are both stochastic functions. CLIMACS has been used successfully to examine effects of disturbances on forest conditions on the Olympic Peninsula (Dale et al. 1986). Simulations were run on several different forest environments using current and projected climatic scenarios.

Several lines of evidence, including results from these model exercises, lead us to propose that responses of established forests to climate change should be muted and have substantial time lags, assuming that the forests are not destroyed or significantly altered by human activities or natural catastrophe. The slow, muted response is due to the ability of established trees to accommodate significant change and to their long life spans. As noted by Brubaker (1986), "[Mature] trees can survive long periods of marginal climate." Furthermore, established forests ameliorate onsite climatic conditions, which also shields them against the effects of the external environment. Hence, barring destruction of the existing stands, changes should be gradual. Model projections confirm this scenario; changes in forest composition diverge only gradually from those projected under current climate for typical sites. Earlier modeling efforts showed similar results (Dale and Franklin 1989).

The most environmentally sensitive stage for western tree species is at the time of seedling establishment, reflected in the muted responses of established forests. As noted by Brubaker (1986), "The long lifespans of trees can slow the retreat of range boundaries, if adults remain in the vegetation several centuries after climatic deterioration makes local conditions unsuitable for seedling establishment." High rates of mortality are typical of germinants and small seedlings, mostly as a result of adverse environmental conditions, such as heat, drought, and frost. Indeed, mortality at the seedling stage may effectively preclude any tree establishment where environmental conditions are severe.

Despite the inertia, gradual compositional shifts can be expected even in established

forests. These will tend to occur along environmental gradients—upward in elevation, northward in latitude, and from southerly to northerly aspects within a locale. Shifts in elevation and aspect are likely to be more rapid and to occur with greater predictability than latitudinal shifts; this is because of the proximity of vegetation zones along topographic transects, whereas valley and mountain barriers may block or slow latitudinal shifts. As others have suggested, we expect that species will typically shift independently, since this is what appears to have happened in the past and it reflects their differing physiological tolerances and susceptibilities to pests and pathogens. As suggested by our model results, typical shifts might be the replacement of Pacific silver fir by western hemlock as the major climax species at middle elevations on the western slopes of the Cascade Range and Olympic Mountains and the loss of western hemlock at lower elevations from decreased moisture availability.

Shifts will not always be simple displacements of one or a few species, however. Surprises (exceptions to our logical predictions) will probably be the rule, as species and environments interact unexpectedly. To a large extent this apparent unpredictability is due to our inability to understand or model all important environmental variables. For example, Woodman's (1987) prediction that Douglas fir will grow to higher elevations under altered climate does not take account of the Douglas fir's aversion to wind-exposed environments, even when moisture and temperature conditions are well within its tolerances. Hence, Douglas fir may not always provide appropriate replacements for the true firs (*Abies* spp.) lost from exposed upper-slope and ridgetop environments.

Competitive interactions between species will also alter predicted responses of individual species based on physiological attributes. Freshwater fish communities provide an example related to species' differing thermal tolerances. In the Pacific Northwest, redbreast shiners (*Richardsonius balteatus*) compete more effectively with juvenile steelhead trout

(*Salmo gairdneri*) as water temperatures increase (Reeves 1987); trout dominate in waters less than 15°C, but shiners dominate at temperatures greater than 19°C, even though temperatures are well within the physiological limits of both species. Competitive interactions of this type could lead to species extinctions long before physiological tolerances are approached.

There will doubtless be community-level as well as individual species responses. One striking change could be the elimination of much of the cold snow zone, the mountain hemlock zone, in the Cascade and northern Sierra Nevada ranges and Olympic Mountains. A deep winter snowpack and short snow-free season characterize this zone, which is important hydrologically. Unfortunately, because mountain tops are smaller than bases, extensive land surfaces are not available to replace the acreage lost by the mountain hemlock zone as temperatures force it up in elevation (e.g., table 19.2). Even where new land is available, substantial lags in forest establishment can be expected at upper timberline; hence, the vegetative mosaic of the subalpine parkland, the upper subzone of the mountain hemlock zone, will not quickly replace itself as the warmer climate moves upslope.

Another community-level change will involve the loss of forest to nonforested communities at lower timberline (i.e., at the hot, dry lower elevation sites). Many sites in northern California and southwestern Oregon (and a scattering of locales farther north) are already near the environmental limits of forest growth. Hotter and drier conditions, coupled with disruption of the forest through fire or other human activities, could shift vegetation on these sites from forest to nonforested types, such as chaparral, or to woodlands dominated by hardwoods, such as oaks (*Quercus* spp.). Sites currently characterized as belonging to the ponderosa pine and Douglas fir series would be candidates for conversion to nonforested conditions.

Some aspects of ecosystem function may respond more rapidly to global change than

composition and structure. Functional changes, such as in productivity, will occur both as the climate warms and dries and as communities and species migrate along environmental gradients. Moreover, functional responses will be linked and multidirectional. For example, aboveground forest production at the dry end of the environmental gradient is likely to decrease with increased temperature. On the other hand, evidence from controlled environment studies indicates that higher levels of CO<sub>2</sub> may result in improved water-use efficiency; hence, tree species that have good stomatal control may maintain or even increase forest productivity by decreasing stomatal aperture while still receiving sufficient influx of CO<sub>2</sub>. Increased evapotranspiration and summer drought probably will increase allocation of photosynthate to below-ground production. In contrast, decomposition in soils is likely to increase with warming because respiration rates will increase and more carbon will be available to decomposers from greater below-ground production. Decomposition under global climate change should lead to reductions in total carbon storage in soils, assuming that the effects of increased temperature are greater than those of decreased soil moisture.

Generally, we would expect the responses of established (intact) forests to be greater in the following cases: in dry rather than moist habitats, at more southerly than northerly latitudes, and in interior than in coastal environments. Changes may be greatest in southwestern Oregon and northern California, where many species are at their physiological limits already, and at high elevations in the area currently characterized by a permanent winter snowpack. We can expect that because of disturbance regimes, the lower elevation (hot and dry) timberline will retreat much more rapidly than upper timberline will advance by colonization of presently unforested slopes. It is certain that there will be many surprises as we are blindsided by unknown interactions between shifting environments and biota. Still, changes in intact,

relatively undisturbed forests will be dwarfed by those occurring in forests stressed by altered disturbance regimes.

#### IV. NEW CATASTROPHIC SCENARIOS: EFFECTS OF ALTERED DISTURBANCE REGIMES

We believe that the most rapid and extensive biotic changes in forests from climate change will be caused by altered disturbance regimes. Disturbances create the conditions for change in ecosystems, effectively doing the work of eliminating the established forest with its inertia, or tolerance of altered climatic conditions. As noted by Brubaker (1986), "[Disturbances] should also mitigate the lagging effects of long tree lifespans by accelerating rates of population decline when climatic change makes conditions unfavorable for seedling establishment."

Altered frequencies, intensities, and locales of catastrophic disturbances are probable under the proposed scenarios of global change. These would include wildfire, storms of all types (including extreme wind conditions and rain-on-snow events), and outbreaks of pests. In fact, the combination of disturbance and climate change will provide a double whammy for the forests of the Pacific Northwest. First, a disturbance destroys the existing forest, which has an ability to resist change. Second, the environment under global change provides conditions for forest reestablishment that may be much more severe than those that existed previously (i.e., drier and hotter environments). We again note that tree regeneration is the stage of forest succession most sensitive to moisture and temperature conditions.

##### A. Wildfire

Increased frequency of fire is certain under the climate change scenario, and greater intensities are probable, at least during a transitional period. A latitudinal gradient in fire frequency exists in the Pacific Northwest because of associated climatic changes. For example, fire return intervals of 114 to 166 years

have been described for the central Oregon Cascade Range (Morrison and Swanson 1990) while intervals of 425 years are reported in the central Washington Cascade Range (Hemstrom and Franklin 1982). Hence, fire frequencies more characteristic of northern California might be expected throughout western Oregon, and frequencies characteristic of west central Oregon could migrate to western Washington. Such shifts could create severe fire threats to resources and problems in fire control as forests with large fuel loadings (high biomass) are subjected to more frequent and, for an interim period, more intense burns.

Frequency and subsequent recovery from fires will probably be strongly influenced by synergisms between human activities and the changed environments. Human uses of the forestscapes, especially timber cutting, increase ignition probabilities, as well as the need for fire control. The effect of intensive management of forest lands is at least as important; young managed forests are apparently more susceptible to catastrophic fire than old-growth forests. For example, during the 1987 wildfires in southwestern Oregon, plantations were affected much more drastically than older forests (Perry 1988). In the Galice and Longwood fires most plantations between the ages of 5 and 25 years (generally the oldest plantings present) were destroyed, while many old-growth stands survived (Perry 1988). A mixed young stand of conifers and hardwoods, which is characteristic of natural stands, may be less vulnerable to fire than pure young conifer stands.

Intensive utilization also reduces or eliminates the biological legacies (such as green trees and coarse woody debris) that contribute significantly to the speed and completeness of forest recovery on burned-over sites. For example, some shrubby angiosperms form mycorrhizae with the same fungal species as many conifers; eliminating these shrubs by forestry practices may reduce the recovery potential of forested sites following catastrophic fire. This occurs in southwestern Oregon where ericaceous shrubs and con-

ifers host some common mycorrhizal fungi; conifer seedlings are disproportionately associated with the shrubs, suggesting that the rich concentration of mycorrhizal inocula enhances their survival (Amaranthus and Perry 1987, Perry et al. 1987).

Hence, higher fire frequencies coupled with the simplifying effects of intensive management could contribute significantly to shifts from forest to nonforest conditions under a hotter, drier climatic regime. Increased fire frequency could also shift some sites from conifer to hardwood dominance, since many hardwood species reproduce readily following fire by sprouting (e.g., tanoak, *Lithocarpus densiflorus*, and Pacific madrone, *Arbutus menziesii*) or seed (e.g., red alder, *Alnus rubra*).

### B. Storm Events

Storm events are important disturbances that have catastrophic effects on both terrestrial and aquatic ecosystems. Shifts in the frequency, intensity, and location of storm events seem likely under global climate change. For example, increased contrasts between oceanic and continental temperatures should produce more intense storms.

Storms with high winds may cause extensive tree mortality by uprooting and breaking trees. Entire stands can be eliminated over hundreds or even thousands of acres, as exemplified by the 1921 blowdown on the western Olympic Peninsula (Buchanan and Englerth 1940), the 1952 blowdowns in the Oregon Coast Ranges (Ruth and Yoder 1953), and the Columbus Day windstorm in 1962 (Lynott and Cramer 1966). Henderson and Peter (1981) identify windstorm, not wildfire, as the primary forest catastrophe on the western Olympic Peninsula, which is also similar to coastal Alaska (Ruth and Harris 1979).

High flows and debris avalanches associated with winter storms are major forces that disrupt and reset stream and river ecosystems and their associated riparian zones (Gregory et al. 1991) to early successional states. Major flood events in the Pacific Northwest are invariably associated with rain-on-snow storms (Harr 1981). Extensive

mountain regions from central California to coastal British Columbia fall into an elevational band known as the "warm snow zone." Significant snow accumulates in these areas during cold periods, but the relatively warm snowpacks melt rapidly when warm wet air masses move in from the Pacific Ocean, producing large snowmelts concurrently with heavy rain. High stream runoffs result in extensive flooding, as in December 1964.

Human activities can accentuate the damage of such storm events. For example, the network of clearcuts and roads created by logging activities contributed significantly to the blowdown suffered in a 1983 windstorm in the Bull Run River drainage of the northern Oregon Cascade Range; approximately 80% of half a billion board feet of blowdown timber was associated with boundaries of clearcuts and road rights-of-way (Franklin and Forman 1987). Similarly, large areas of clearcutting can magnify the effects of rain-on-snow flood events (Harr 1981); typically snow accumulations are larger and more susceptible to warming and melting in recently cutover areas than on forested sites.

Hence, alterations in the frequency, intensity, and location of major storm events as a result of global warming could have profound consequences for forests and associated rivers.

### C. Pests and Pathogens

New and intensified problems with insects and diseases are probable under global change. In some cases these will result from more favorable environments for the establishment and spread of a particular pest. In other cases problems will result from the indirect effects of warming as reflected in increased tree stress.

The possible expansion of the balsam woolly aphid (*Adelges piceae*) into stands of subalpine fir (*Abies lasiocarpa*) is a good example of how altered climates could produce a major insect epidemic. The aphid is an introduced pest that has been a serious problem on Pacific silver fir and low-elevation occurrences

of subalpine fir in the Pacific Northwest (Mitchell 1966, Franklin and Mitchell 1967). It has been effectively restricted to low and middle elevations by its temperature requirements; the second generation of the aphid must reach the first instar stage to survive the winter. The subalpine zone of the coastal mountains rarely provides the necessary heat, so too few of the aphid attain the critical stage during most years to produce dense populations (Mitchell 1966).

A 2.5°C increase in mean temperature (the low end of the climate change scenario) would allow the aphid to reproduce and spread at the higher elevations where subalpine fir is a major stand component. Mature subalpine fir have low resistance to the aphid (Mitchell 1966). Consequently, high levels of subalpine fir mortality are probable, perhaps comparable to those experienced in the Fraser fir (*Abies fraseri*) populations in the southern Appalachian Mountains—nearly 100% of adult individuals (Dale et al. 1991).

Increased numbers and intensities of pest outbreaks can be expected as established forest stands are subjected to increasing physiological stresses associated with global warming (Mattson and Haack 1987). Even under conditions of stable climate the majority of pest outbreaks are associated with increased host stress. Furthermore, pests and pathogens are often highly vagile; hence, they can shift rapidly in response to altered environmental conditions (Schowalter et al. 1986).

As with fire and storm, undesirable synergisms between altered disturbance regimes and human activities are probable with insects and disease. Forestry practices have predisposed many forests to outbreaks. One example is the recent outbreak of southern pine beetle (*Dendroctonus frontalis*) in the extensive, pure, even-aged stands of southern pines that have been created in the southeastern United States (Schowalter et al. 1981). The simplified forest stands created by intensive management tend to be more vulnerable to outbreaks of pests than natural stands (Franklin et al. 1989, Schowalter 1988). In

comparison, J. D. Lattin and P. Oman (1983) have noted how established forests, especially old-growth forests, are buffered from rapid floral and faunal change.

#### D. Summary on Disturbances

We conclude that altered disturbance regimes will interact with global warming to produce major change in the forestscapes of the Pacific Northwest long before climate change alone would produce significant change in established forests. Disturbances will create opportunities for change by reducing the inertia of established forests. Hence, disturbances can be viewed positively as events that speed adjustments of vegetation to current environmental conditions. On the other hand, these changes could be highly disruptive in the short- and mid-term. Global warming creates more severe conditions for forest reestablishment, which may cause drastic shifts in the composition and function of the postdisturbance forests. Some probable overall effects of these changes include a net shift in area from forest to nonforest vegetation, net loss of biotic diversity as some species fail to track suitable environments, and minor additions to atmospheric CO<sub>2</sub> as organic matter accumulations decrease on forest sites. Transitions will be a problem because forest destruction will almost certainly occur more rapidly than forest reestablishment, especially at the lower forestlines. In general, natural forest ecosystems, with their greater compositional and functional redundancy, are expected to show greater resistance to change and to recover more rapidly following disturbance than intensively managed forests.

Research is critically needed on some currently obscure aspects of climate change and ecological responses. Information on changes in factors affecting the frequency, intensity, and locale of major disturbances is essential. For example, what are predicted magnitudes and intensities of summer drought periods? What are the probabilities for repeated drought years? Are changes in the frequency and tracks of storms with high

winds likely? Information on seasonal changes in climate are also important to assess both direct and indirect effects of climate change.

#### V. IMPLICATIONS FOR FOREST MANAGERS AND APPLIED ECOLOGISTS

Environmental changes such as those proposed here under global warming have profound implications for managers and applied ecologists. Significant changes will be necessary in the way we perceive and manage those lands devoted to commodity production, as well as those devoted to preservation, if we are to have some reasonable hope of success in preserving biological diversity.

First, lands that are devoted to production of commodities—the managed timberlands, rangelands, and agricultural lands—dominate our landscape; yet, in planning for biological diversity we have often overlooked these lands and instead focused on reserves or primeval habitats. Typically, conservationists and land managers both view biological diversity as a question of setting aside resources. It is critical that we begin to take, as scientists and a society, a more critical and holistic view of how the commodity lands, our seminatural landscape matrix, are managed. These are the bulk of our lands, and as such, they form a vast ocean in which ecological preserves are located and also contain much, perhaps most, of the remaining biological diversity, at least in the temperate zones. Consequently, the commodity lands are the battleground where the war for biodiversity will ultimately be won or lost, especially with the drastic environmental shifts that global warming will bring. We need to alter management practices that produce ecologically depauperate landscapes and thereby reduce indigenous diversity and maximize the isolation of preserves.

Traditional forest management, for example, tends to reduce genetic, structural, temporal, and spatial diversity by emphasizing efficient timber production through simplification (Franklin et al. 1989). Traditional sil-

vicultural systems have focused almost exclusively on the trees—removal of wood products while providing for reestablishment of the next tree crop. Foresters have been innovative in developing practices to accommodate other ecological values, such as provision of dead trees for wildlife, but this has been a largely piecemeal adaptation to the emerging needs of ecological forestry. Foresters need to develop and implement a new forestry that has as its philosophical underpinning the maintenance of complex forest ecosystems and not simply the reestablishment of trees. Examples of specific silvicultural practices might include maintenance of structural diversity by providing for coarse woody debris (standing dead trees and downed boles) and development of stands of mixed composition and structure (Franklin et al. 1989). Such practices are already being applied on some federal, state, and private lands in the Pacific Northwest. At the landscape level foresters can adopt spatial patterns for cutting that reduce forest fragmentation, select patch sizes relevant to the needs of interior species, and incorporate natural patches and corridors (Franklin and Forman 1987). Approaches of this sort are being tried in several forested regions of the United States; for example, an approach called minimum fragmentation is being tested in western Oregon (Hemstrom 1989).

Our perspectives on the ecological reserves—national parks, wilderness, research natural areas, and nature reserves—also may need some readjustment. These areas remain critical to maintenance of biological diversity, but they will not provide adequately for biological diversity in the face of the climate scenarios that have been presented. In fact, even without climate change they probably could not do the job alone, since their representation of diversity is incomplete, their total acreage is small, and, most important, they are increasingly isolated within hostile landscapes. These reserves will provide society with rich reservoirs of ecological diversity to conserve and utilize in coping with global warming.

If environmental changes reach the magnitude proposed in the climate scenarios, the objectives and management approaches on ecological reserves must be drastically revised. Under global warming, using naturalness or natural processes as a guiding principle will be of limited value in maintaining biological diversity. To speak of mitigating such effects is ridiculous. As habitats and environments migrate from reserves, as catastrophes destroy relict ecosystems, as species disappear, we must become first-class ecological engineers or risk losing large components of the diversity that now resides in the reserved lands.

We conclude that any strategy for preserving biological diversity, particularly in the face of global warming, must involve a comprehensive approach to both commodity and reserved lands. Commodity lands, the seminatural matrix, must be managed with more consideration for ecological values, including those on the reserved lands that they surround. These landscapes must nurture biological diversity, first by retaining more elements of diversity within the seminatural matrix and second by easing the passage of other organisms. A less hostile matrix, one more accommodating to migrating organisms, would also drastically increase the opportunity for ecological dialogue—reciprocal movement of organisms, materials, and services—between reserved and intensively managed landscapes, to their mutual benefit. Reserved lands must be viewed as source areas for diversity but not necessarily as permanent residences for that diversity. Intensive management efforts involving both types of land will be necessary as society undertakes ecological triage, a damage-control exercise on biological diversity threatened by global climate change. As ecologists, managers, and a society, we will have to become knowledgeable, creative, innovative, overt, and holistic as we collaborate with nature to save biological diversity in the face of global warming.

#### REFERENCES

- Agee, J. K., and R. Flewelling. 1983. A fire cycle model based on climate for the Olympic Mountains, Washington. In *Seventh Conference on Fire and Forest Meteorology*. Boston, Mass.: American Meteorological Society.
- Amaranthus, M. P., and D. A. Perry. 1987. Effect of soil transfer on ectomycorrhiza formation and the survival and growth of conifer seedlings on old, nonreforested clear-cuts. *Can. J. Forest Res.* 17:944.
- Atzet, T., and D. L. Wheeler. 1984. *Preliminary Plant Associations of the Siskiyou Mountain Province*. Portland, Oreg.: USDA Forest Service Pacific Northwest Region.
- Barnosky, C. W., P. M. Anderson, and P. J. Bartlein. 1987. The northwestern U.S. during deglaciation: Vegetational history and paleoclimatic implications. In *North America and Adjacent Oceans during the Last Deglaciation*, W. F. Ruddiman and H. E. Wright, Jr., eds., *Geology of North America*, vol. K-3, pp. 289–321. Boulder, Colo.: Geological Society of America.
- Brubaker, L. B. 1986. Responses of tree populations to climatic change. *Vegetatio* 67:119.
- Brubaker, L. B. 1988. Vegetation history and anticipating future vegetation change. In *Ecosystem Management for Parks and Wilderness*, J. Agee and D. Johnson, eds. Seattle: University of Washington Press.
- Buchanan, T. S., and E. H. Englerth. 1940. Decay and other losses in wind-thrown timber in the Olympic Peninsula, Washington. *USDA Technical Bulletin 733*. Washington, D.C.: U.S. Department of Agriculture.
- Dale, V. H., and J. F. Franklin. 1989. Potential effects of climate change on stand development in the Pacific Northwest. *Can. J. Forest Res.* 19:1581.
- Dale, V. H., and M. Hemstrom. 1984. CLIMACS: A computer model of forest stand development for western Oregon and Washington. *USDA Forest Service Research Paper PNW-327*. Portland, Oreg.: Pacific Northwest Research Station.
- Dale, V. H., M. Hemstrom, and J. Franklin. 1986. Modeling the long-term effects of disturbances on forest succession, Olympic Peninsula, Washington. *Can. J. Forest Res.* 16:56.
- Dale, V. H., R. H. Gardner, D. L. DeAngelis, C. C. Eagar, and J. W. Webb. 1991. Elevation-mediated effects of the balsam woolly adelgid on the southern Appalachian spruce-fir forests. *Can. J. Forest Res.* 21:1639.
- Davis, M. B. 1986. Climatic instability, time lags, and

- community disequilibrium. In *Community Ecology*, J. Diamond and T. J. Case, eds., pp. 269-284. New York: Harper and Row.
- Delcourt, P. A., and H. R. Delcourt. 1987. Long-Term Forest Dynamics of the Temperate Zone. New York: Springer-Verlag.
- Franklin, J. F. 1988. Pacific Northwest forests. In *North American Terrestrial Vegetation*, M. Barbour and D. Billings, eds., pp. 103-130. New York: Cambridge University Press.
- Franklin, J. F., and C. T. Dyrness. 1973. Natural vegetation of Oregon and Washington. USDA Forest Service General Technical Report PNW-8. Portland, Oreg.: Pacific Northwest Forest and Range Experiment Station.
- Franklin, J. F., and R.T.T. Forman. 1987. Creating landscape patterns by forest cutting: Ecological consequences and principles. *Landscape Ecol.* 1:5.
- Franklin, J. F., and R. G. Mitchell. 1967. Successional status of subalpine fir in the Cascade Range. USDA Forest Service Research Paper PNW-46. Portland, Oreg.: Pacific Northwest Forest and Range Experiment Station.
- Franklin, J. F., and R. H. Waring. 1981. Distinctive features of the northwestern coniferous forest: Development, structure, and function. In *Forests: Fresh Perspectives from Ecosystem Analysis*, R. H. Waring, ed., pp. 59-86. Corvallis: Oregon State University Press.
- Franklin, J. F., W. H. Moir, M. A. Hemstrom, S. E. Greene, and B. G. Smith. 1988. The forest communities of Mount Rainier National Park. USDI National Park Service Scientific Monograph Series 19.
- Franklin, J. F., D. A. Perry, T. D. Schowalter, M. E. Harmon, A. McKee, and T. A. Spies. 1989. Importance of ecological diversity in maintaining long-term site productivity. In *Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems*, D. A. Perry et al., eds., pp. 82-97. Portland, Oreg.: Timber Press.
- Gholz, H. L. 1982. Environmental limits on above-ground net primary production, leaf area, and biomass in vegetation zones of the Pacific Northwest. *Ecology* 63:469.
- Greene, S. G., and M. Klopsch. 1985. Soil and air temperatures for different habitats in Mount Rainier National Park. USDA Forest Service Research Paper PNW-342. Portland, Oreg.: Pacific Northwest Research Station.
- Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins. 1991. An ecosystem perspective of riparian zones. *Bioscience*: in press.
- Grier, C. C., and S. Running. 1977. Leaf area of mature northwestern coniferous forests: Relation to site water balance. *Ecology* 58:893.
- Hansen, J., I. Fung, A. Lacis, S. Lebedeff, D. Rind, R. Ruedy, G. Russell, and P. Stone. 1988. Prediction of near-term climate evolution: What can we tell decision-makers now? In *Preparing for Climate Change*, Proceedings of the first North American conference on preparing for climate change: A cooperative approach, J. C. Topping, Jr., ed., pp. 35-47. Washington, D.C.: Government Institutes.
- Harr, R. D. 1981. Some characteristics and consequences of snowmelt during rainfall in western Oregon. *J. Hydrol.* 54:277.
- Hemstrom, M. 1989. Alternative timber harvest patterns for landscape diversity. *COPE Report* 3(1): 8. (College of Forestry, Oregon State University, Corvallis.)
- Hemstrom, M. A., and J. F. Franklin. 1982. Fire and other disturbances of the forests in Mount Rainier National Park. *J. Quatern. Res.* 18:32.
- Henderson, J. A., and D. Peter. 1981. Preliminary plant associations and habitat types of the Quinalt Ranger District, Olympic National Forest. Portland, Oreg.: USDA Forest Service Pacific Northwest Region.
- Lattin, J. D., and P. Oman. 1983. Where are the exotic insect threats? In *Exotic Plant Pests and North American Agriculture*, C. Wilson and C. Graham, eds., pp. 93-137. New York: Academic Press.
- Leverenz, J. W., and D. J. Lev. 1987. Effects of carbon dioxide-induced climate changes on the natural ranges of six major commercial tree species in the western United States. In *The Greenhouse Effect, Climate Change, and U.S. Forests*, W. E. Shands and J. S. Hoffman, eds. Washington, D.C.: Conservation Foundation.
- Lynott, R. E., and O. P. Cramer. 1966. Detailed analysis of the 1962 Columbus Day windstorm in Oregon and Washington. *Monthly Weather Rev.* 94: 105.
- Mather, J. R. 1974. *Climatology: Fundamentals and Applications*. New York: McGraw-Hill.
- Mattson, W. J., and R. A. Haack. 1987. The role of drought in outbreaks of plant-eating insects. *Bioscience* 37:110.
- Mitchell, R. G. 1966. Infestation characteristics of the balsam woolly aphid in the Pacific Northwest. USDA Forest Service Research Paper PNW-35. Portland, Oreg.: Pacific Northwest Research Station.
- Morrison, P., and F. J. Swanson. 1990. Fire history and pattern in a Cascade Range landscape. USDA Forest Service Research Paper PNW-GTR-254-77.

- Portland, Oreg.: Pacific Northwest Research Station.
- Perry, D. A. 1988. Landscape pattern and forest pests. *Northwest Envir. J.* 4:213.
- Perry, D. A., R. Molina, and M. P. Amaranthus. 1987. Mycorrhizae, mycorrhizospheres, and reforestation: Current knowledge and research needs. *Can. J. Forest Res.* 17:929.
- Reeves, G. H., F. H. Everest, and J. D. Hall. 1987. Interactions between the redbreasted sunfish (*Richardsonius balteatus*) and the steelhead trout (*Salmo gairdneri*) in western Oregon: The influence of water temperature. *Canadian Journal of Fisheries and Aquatic Sciences* 44:1603.
- Ruth, R. H., and A. S. Harris. 1979. Management of western hemlock-Sitka spruce forests for timber production. USDA Forest Service General Technical Report PNW-88. Portland, Oreg.: Pacific Northwest Research Station.
- Ruth, R. H., and R. A. Yoder. 1953. Reducing wind damage in the forests of the Oregon Coast Range. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station Research Paper 7. Portland, Oreg.: Pacific Northwest Research Station.
- Schowalter, T. D. 1988. Forest pest management: A synopsis. *Northwest Envir. J.* 4:313.
- Schowalter, T. D., R. N. Coulson, and D. A. Crossley. 1981. Role of southern pine beetle and fire in maintenance of structure and function of the southeastern coniferous forest. *Envir. Entomol.* 10:721.
- Schowalter, T. D., W. W. Hargrove, and D. A. Crossley, Jr. 1986. Herbivory in forested ecosystems. *Ann. Rev. Entomol.* 31:177.
- Shugart, H. H. 1984. *A Theory of Forest Dynamics*. New York: Springer-Verlag.
- Tsukada, M. 1982. *Pseudotsuga menziesii* (Mirb.) Franco: Its pollen dispersal and late Quaternary history in the Pacific Northwest. *Jap. J. Ecol.* 32:159.
- Waring, R. H., and J. F. Franklin. 1979. Evergreen coniferous forests of the Pacific Northwest. *Science* 204:1380.
- Woodman, J. N. 1987. Potential impact of carbon dioxide-induced climate changes on management of Douglas-fir and western hemlock. In *The Greenhouse Effect, Climate Change, and U.S. Forests*, W. E. Shands and J. S. Hoffman, eds. Washington, D.C.: Conservation Foundation.
- Zobel, D. B., A. McKee, G. M. Hawk, and C. T. Dyrness. 1976. Relationships of environment to composition, structure, and diversity of forest communities of the central western Cascades of Oregon. *Ecol. Monogr.* 46:135.

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