Chapter 8

# Managing Redwoods

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Previous chapters have made a variety of points relevant to the management of redwood forests. Four general lessons stand out: First, primary old-growth redwood forests are immensely valuable for biological, aesthetic, and other reasons and have become rare in the region after a century and a half of logging. As these forests have declined by more than 95 percent since European settlement, so have many of the species associated with them. Some of the structures, ecological processes, and biological assemblages of old-growth forests, such as those of the forest canopy (see chap. 3 and 4), are dimly understood and difficult to replicate in younger forests. Therefore, protecting as much as possible of the remaining old growth is a sensible policy.

Second, as will be elaborated further in this chapter, stands of second-growth redwoods (and, in some cases, third growth) that retain structural legacies from former old-growth stands, or that have regained some of these structural quail-

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*Author contributions:* Thornburgh, lead author and organizer; Noss, writing and editing throughout; Angelides and Olson, management practices on commercial forests; Euphrat, box on Big Creek; Welsh, appendix on forest practices and riparian/aquatic ecosystems.

ties over time or through management, are also valuable; many "old-growth" species seem able to persist in these stands. Second- and third-growth redwood forests currently dominate the redwood region. These stands will become more valuable as they age and as more of the region is converted to nonforestland uses.

Third, the remaining redwoods on private lands, a small proportion (estimated as < 1 percent) of which are old growth, cannot all be placed in protected areas. Funds for land acquisition by Save-the-Redwoods League and other conservation interests are limited and must be devoted to those stands and landscapes of highest conservation value (see chap. 7). Difficult decisions must be made. Moreover, redwood produces a beautiful wood that is legitimately used by people for many purposes. Sustainable production of this commodity is desirable.

Finally, however, most previous logging of redwood forests has not been sustainable and has destroyed many biological and other values. New silvicultural systems, based on better understanding of redwood forest ecology would go a long way toward avoiding degradation of forests and encouraging sustainability. Some of these systems can be used to hasten the development of old-growth structural conditions and associated species in second- and third-growth forests and plantations. These points are the premises of this chapter.

This chapter reviews management practices in redwood forests, from prescribed burning, used to restore and maintain natural qualities in old-growth stands in parks, to new silvicultural techniques aimed at sustainable forestry on private lands. The main emphasis here is on silviculture, ranging from traditional even-aged and selection management to new, alternative approaches. New approaches strive to mimic natural disturbance regimes in order to maintain the total biodiversity of the ecosystem, produce clean water and air, store carbon, and provide products useful to society.

## Management of Redwood Parks

Many people assume that management of parks and other nature reserves is an oxymoron, believing these areas are best left alone to take care of themselves. Paradoxically, however, in landscapes where natural processes have been disrupted, some kind of management is usually necessary to maintain the natural qualities of the ecosystem. This is true for the redwood parks, where, among other problems, the natural disturbance regime-especially fire-no longer operates as it once did.

### *Management of Old-Growth Reserves*

As explained in chapter 4, recurring fire is a natural feature of redwood forests. The relationship between redwood forests and fire is complex, however. Depending on site conditions, either too much or too little fire (in intensity or frequency) can place redwood trees at a disadvantage relative to competing tree and shrub species (see box 4.3). In the old-growth redwood forests of Redwood National Park, and in the various redwood state parks, managers are attempting to reintroduce the natural fire cycle through controlled burns. The intent is to restore and perpetuate the natural structure and composition of the ecosystem.

Studies indicate that the pre-European, mean fire-return interval in some southern redwood forests was eight years (Brean and Svensgaard-Brean 1998), although it varied among sites in the region. Greenlee and Langenheim (1990) found intervals ranging from 17 to 175 years in southern redwood forests (see chap. 4). Since 1978, state park personnel have burned 100-140 ha of southern redwood forests annually, in a shifting pattern so that every site is burned approximately every eight years, in an attempt to return these forests to a more natural condition. After a century of fire suppression, however, large amounts of duff and litter have accumulated around the bases of trees. Combustion of this litter could potentially kill even large trees. To prevent mortality to the large trees, this layer is removed before a prescribed burn, accompanied by thinning of the understory. Although promising, the ecological consequences of these treatments in Big Basin Redwood State Park and elsewhere have not been evaluated (W J. Berry, Cal. Dept. Parks and Rec., pers. comm.).

In the central redwood forest, at Humboldt Redwoods State Park, a fire-history study indicated a fire rotation of 26.2 years before European settlement (Stuart 1987). Again, however, considerable variation existed (see chap. 4). Many of these fires were probably set by the Sinkyone Indians who inhabited the region. No major fires have occurred since 1940, resulting in the accumulation of greater-than-normal levels of large and live fuels and increasing the probability of a large, intense fire. The California State Parks agency seeks to burn 2,000-2,800 ha of the central redwood forests annually (W J. Berry, pers. comm.). In Humboldt Redwoods State Park, the objective is to prescribe-burn 300 ha of old growth and a smaller area of second-growth forest each year. This reintroduction of fire, meant to simulate the natural fire cycle, is viewed as essential to reduce fuels, expose the understory, prepare seedbeds, release seeds, and control nonnative plants (Brean and Svensgaard-Brean 1998). Prescribed burns have resulted in lower levels of litter fuels and live sclerophyllous vegetation, with no serious charring of old-growth redwood or Douglas-fir (Stuart 1985). Some of the older second growth has been underburned to accelerate the development of old-growth structural conditions.

Fire is thought to have a moderate ecological role in the northern redwood forest (Olson et al. 1990). Nevertheless, a study in Redwood National Park adjoining Prairie Creek State Park suggested a mean fire return interval of eight years before European settlement (S. Underwood, Redwood National Park, pers. comm.). Other studies have documented a great range of intervals, depending on distance from the coast and other factors (see chap. 4). Light ground fires that do not open the canopy favor western hemlock regeneration but usually eliminate older hemlocks from the stand. Redwood, grand fir, and tanoak appear to maintain their status with or without fire (S. D. Veirs, pers. comm.); in the absence of fire, redwood can regenerate on downed logs or mineral soil. At Redwood National Park, the goal is to reintroduce the natural role of fire while limiting the risk to resources on adjacent lands. The area of old-growth forest prescribed-burned in the park has generally increased each year. In 1997 and 1998, park personnel burned 35 ha. Plots have been established to monitor the effects of the burn, which include the amount of burnt bark and cambium on large and small trees and the effects of fire on understory tree seedlings and herbaceous vegetation (S. Underwood, pers. comm.). Preliminary observations suggest that old-growth stands managed with frequent, low-intensity fires show reduced biodiversity, including understory flora, canopy trees, and evidence of animals (D. Thornburgh, unpub. data), though fires of higher intensity produce a more diverse canopy structure and higher biodiversity. No burning has occurred in the northern Redwood State Parks: Prairie Creek, Del Norte, and Jedediah Smith.

Another management issue in the northern redwood region, as elsewhere, is exotic plants (see chap. 3, box 3.2). Numerous exotic plant species, including English and Cape ivy and Spanish heath, have become established in the old-growth stands of Redwood National Park, threatening to upset the biological community. The park's exotic plant management plan proposes eradication by hand and biocontrol (Fritzke and Moore 1998). The relationship between exotic plant invasion and fire in redwood forests has not been well documented.

### *Management of Second-Growth Reserves*

About 18,800 ha in Redwood National Park, or 63 percent of its total area, is second-growth redwood-Douglas-fir forest. Most of these stands regenerated from old-growth forests that were harvested in the 1950s and 1960s using the seed-tree method for redwood regeneration and aerial seeding for regeneration of Douglas-fir. Some cutting also took place in the 1970s. In 1987, these stands had a conifer density of 3,303-4,525 stems/ha, with 3,158 hardwood stems/ha (Mastrogiuseppe and Lindquist 1996).

A study was initiated in the park in 1968 to determine the efficacy of thinning second growth for the restoration of old-growth characteristics. The treatments thinned selected stands to densities in the range of 250-2,500 stems/ha (Harrington 1983). After thirty years, the understory shrubs huckleberry, Oregon grape, salal, and rhododendron were at the same density as in the old-growth stands. Understory birds also had equivalent abundance in thinned plots and old-growth forests (Menges 1994). Growth of trees in thinned plots was four times the growth in unthinned plots. Redwood National Park initiated further thinnings in 1978, which have accelerated the growth rates of trees and increased understory shrub biomass (S. Veirs, pers. comm., 1998). Thinned plots are developing some of the characteristics of old growth more rapidly than an untreated second-growth stand. The results of these studies suggest that, at least for the characteristics measured, thinning is a useful tool in the restoration of old-growth forests.

Old second-growth forests also occur in some of the state parks. Most of these stands are unmanaged. As noted earlier, however, portions of Humboldt Redwoods State Park have been underburned to hasten the development of old-growth structure. Also, in state parks in the southern redwoods section, second-growth stands are thinned to reduce the tree density from 2,000-3,000 stems/ha to 150-200 stems/ha before the understory can be burned. The structural characteristics of old-growth forests appear to be developing more quickly when stands are thinned.

A portion of the Arcata Community Forest is dedicated as a nature reserve. The area that is now in the reserve was logged in 1890 by handsaws, log-bark peeling, and slash burning, yarded by oxen, and left to regenerate. The reserve today is a dense forest of a few residual, old redwood trees and a mixture of 108-year-old redwood, Douglas-fir, western hemlock, grand fir, and Sitka spruce. The stand structure is being altered by a shifting pattern of relatively small patchy disturbances caused by infrequent windstorms. Storms with winds severe enough to topple large trees occur almost every year, with a high of thirteen storms in 1981. Blowdowns have created numerous canopy gaps, which provide resources for establishment of grand fir, western hemlock, and redwood in the understory and increased height growth of individual trees in lower and mid-canopy positions. These wind disturbances are slowly converting this stand into a typical northern redwood old-growth forest, with abundant coarse woody debris and an upper canopy dominated by redwoods.

The primary anthropogenic impact to the Arcata Community Forest reserve today is human recreational use, which is heavy, accompanied by a slow invasion of such nonnative plants as English ivy and holly (though this invasion has been slowed by volunteers hand-pulling the exotic plants). Most recreational use is confined to hiking trails; however, trampling impacts are noticeable in the forest understory, particularly in the riparian zones along small streams. Frisbee golf playing, illegal camping, and off-trail hiking are the major sources of impact. Some of the affected areas have been planted with sword fern and oxalis and covered with slash to discourage off-trail use. Other second-growth nature reserves experience so much human impact that the owners have given up trying to keep them natural; an example is the redwood forest near the Eureka Zoo.

The small size of these nature reserves in the context of an increasingly urbanized landscape creates uncertainty with respect to their ability to maintain a natural state over the long term. The heavy recreational use, noise, exotic plants, feral cats, and other influences stress habitat conditions and probably populations of some species within the forests. The surrounding land uses, such as urban/suburban development and short-rotation, even-aged forestry, are slowly turning these reserves into isolated islands of old trees with heavily altered understories. Nearby residential development already has limited the ability of reserve managers to employ prescribed burning as a management tool. It is too early to forecast long-term effects of these various landscape changes on the redwood forests, but they are unlikely to be positive.

In large second-growth reserves, such as some of the Redwood National Park units and smaller nature reserves, the forests are increasingly unlikely to develop natural cohorts of multistoried conifers, considered to be typical of old growth (see chap. 4). In most cases, stand development in today's patches of variable-density seedling, shrub-dominated, young forests will not lead to the same kinds of stands and habitats as those produced by natural succession (Tappeiner et al. 1997). Reasons for altered stand development include the following, in various combinations: (1) introduction of nonlocal genotypes; (2) lack of fire, resulting in dominance by different species; (3) establishment of exotic species, both flora and fauna; (4) timber harvest, which has changed species composition and seed supply, favoring the development of shrubs and hardwoods capable of vigorous sprouting; (5) establishment of stands after logging that are often more heavily and uniformly stocked with western hemlock and Douglas-fir than were the original stands; (6) change in climate or weather patterns since the time when the present old-growth forests developed; and (7) suburbanization of scattered blocks of second-growth, with accompanying lawns, roads, and domestic animals.

## Silviculture in Redwoods: Incentives and Disincentives

If redwood forest is to remain a primary land cover in the redwood region, silviculture must be both ecologically responsible and economically viable. Approaches to timber management in redwood forests are dictated by current technologies, economic factors, forest practice rules, social concerns. and the condition of the forests themselves. The cost of managing private lands for harvestable redwoods has been increased by environmental and timber harvest regulations, including the Endangered Species Act and various state laws. It is often argued that increasing regulation has driven small landowners to convert their land from forest to residential development. Although this is true in some circumstances, the major factor in most conversion probably has been increasing land values in the vicinity of urban areas. Outside of urban areas and major highways, little conversion has occurred. Nevertheless, conversion of redwood forests to subdivisions is on the increase and undoubtedly is more destructive environmentally than properly conducted timber harvest; furthermore, the loss is essentially permanent (Anderson 1998).

Historically, silviculture has focused on site-specific or stand-specific prescriptions. It has become increasingly clear, however, that to meet conditions of ecological sustainability, managers must look beyond the individual stand and develop prescriptions that incorporate a mix of stand-specific treatments that will ultimately achieve desired future conditions on the landscape scale. The "big picture" view so necessary for conservation of the biological values of redwood forests (see chap. 7) therefore is also necessary for improved management of redwoods for timber. A big-picture approach requires the flexibility to apply a broad range of stand-specific management treatments and a decision-analysis process adequate to determine the appropriate mix of management activities across the landscape and through time. The financial viability of private forest ownership depends on the health of the region's timber economy, a rational regulatory structure, and most important in the long term, a healthy forest ecosystem.

Because most of the remaining redwood forests are on private lands—managed both by large corporations and small nonindustrial landowners--these owners must have some certainty that their long-term investments in forests are secure; otherwise, they might invest in opportunities such as residential development (where feasible). For a small owner, the cost of complying with regulation can be 25-50 percent of revenues. Blencowe (1998) suggests that streamlining the state regulation process, through "fast-track" Timber Harvest Plans for forest owners who are certified as practicing sustainable forestry, would help to preserve forestland in the redwood region. Standards for certification of forests in the Pacific states are not fully developed and remain controversial, however, especially for harvest of residual old-growth trees and issues concerning landscape ecology.

The California Forest Practices Act of 1973 mandated that nonfederal landowners and managers practice forestry in ways that will protect land productivity and public resources. The Timberland Productivity Act of 1982 added provisions for sustainable harvest practices. The California Environmental Quality Act of 1970, the Porter Cologne Water Quality Act of 1969, and the California Endangered Species Act of 1984 all aim at protecting public resources and are implemented through state regulation, particularly the California Forest Practice Rules. Together, these laws and rules are supposed to govern silvicultural practices by requiring that forest practices protect soil productivity and water quality, that practices be sustainable, and that specified stocking levels are achieved and maintained

Despite the originally good intentions of the laws and rules governing forest practices, many observers believe that the rules are too weak-especially for the protection of riparian/aquatic ecosystems-and that enforcement is often lacking in the redwood region (see appendix 8.1). Evidence for the cynical view is abundant: most of the streams in the redwood region have been declared "impaired" by sediment, listings of species under endangered species laws are on the increase, and public conflicts over forest management issues are escalating. The incentives and disincentives that influence forest practices and forest management decisions in the region apparently need further development to achieve true sustainability of forest ecosystems.

## Traditional Silvicultural Systems

Traditional silvicultural systems currently being applied in the redwood region can be lumped into two general categories: even-age (e.g., clear-cutting) and uneven-age (e.g., selection) systems. The current California State Forest Practice Rules make this distinction; however, both systems can result in highly variable landscape patterns and stand structure depending on how they are implemented. No definitive research is available to compare timber yields or wildlife habitats provided by even-age versus uneven-age systems in redwood forests. Nevertheless, the two systems normally result in distinctly different patterns and structures; thus, they provide habitats for different assemblages of species through time.

### *Even-Age Systems*

Clear-cutting is the most widely used system of silviculture in the redwood region. Removal of all trees except the very smallest during harvest permits easier site preparation, slash disposal, and control of species composition and stocking (Helms 1995). Clear-cutting also provides an open, sunny environment for the new stand, which promotes rapid growth of redwoods. Even after stands achieve crown closure, redwood trees continue to grow and develop rapidly, making continued management investment to enhance their growth attractive. Typically, second-growth redwood stands are harvested at sixty to eighty years; however, the culmination of mean annual increment (the point of maximum average productivity over time) does not occur until the stands are more than one hundred years old.

Because of abundant sprouting redwoods, hardwood stumps, logging slash, and residual vegetation on highly variable terrain and site conditions, hand planting of seedlings in clear-cuts to create "row plantation monocultures" is usually impractical. Grasses, forbs, shrubs, and hardwood trees invade most clear-cuts soon after logging. The rapid development of vegetation provides food and cover for many animal species adapted to early seral vegetation.

The shelterwood and seed-tree systems of harvesting and regenerating redwood stands is similar to the clear-cut method in that most trees except the very smallest are initially harvested, but in this case an overstory of seed trees is left to provide seed and shelter for the next stand of trees. California Forest Practice Rules specify the number and spacing of seed and shelterwood trees to be retained in this system. Often five to ten years before harvest, some trees are removed around the intended seed trees to help them become more windfirm. Once a new stand is established under the seed trees, the seed trees are removed, usually within five to ten years following the harvest of the overstory.

Seed tree and shelterwood systems can be used to facilitate regeneration of species other than redwood. Indeed, the seed tree system usually has been more successful for regeneration of Douglas-fir than of redwood. Redwoods have unpredictable seed crops, seed viability is low, and shelter is not needed to enhance sprout development (Helms 1995). Furthermore, redwood seedlings are extremely vulnerable to infection by damping-off and *Botrytis* fungi during their first year (Hepting 1971).

The removal of seed trees after the new stand is established usually causes some damage to the young trees; often 10-25 percent of the remaining trees are damaged. Retention of the overstory throughout the next rotation, either for seed tree or shelterwood systems, will provide habitat elements (i.e., large trees and subsequent coarse woody debris) that might otherwise be missing from a managed landscape. Such an approach was recommended (Oliver et al. 1996) and is currently being implemented on the Jackson Demonstration State Forest.

Bruce (1923) developed "normal" yield tables for fully stocked redwood stands. Such yield tables indicate how even-age redwoods might grow under intense management, but up to the present time few stands have been managed in this manner. Lindquist and Palley (1963) developed empirical yield tables (growth projections) for well-stocked (though not necessarily fully stocked) young-growth redwood stands over the range of site-quality conditions found in the redwood region. They projected that redwoods grown 100 years yielded more than 3,500 board-feet per acre (35 $m^3$/ha) per year on high-productivity lands, but barely more than 500 board-feet (5 $m^3$/ha) per year on low-productivity lands.

As noted earlier in the review of park management, thinning of second-growth stands can accelerate development of old-growth characteristics. Thinning also has silvicultural value. Typically, even-age systems require intermediate treatment to ensure high productivity over time. Precommercial thinning, combined with control of invading hardwoods and shrubs ("brush") is often needed during early stand development to reduce competition between noncommercial species and the young stand of redwoods. Following clear-cutting or a seed-tree cut, red alder from seed and Pacific madrone and tanoak from sprouts are the hardwoods that compete most commonly with redwood in early stand development.

Redwood responds well to commercial thinning (Cart 1958; Oliver et al. 1996). One or two commercial thins are often applied at some point after the stand is thirty years old to remove some of the growing stock so the remaining trees have more room to grow. The overall yield over the length of the rotation is increased by this practice, and the average tree diameter of the stand cut at the end of the rotation is greater. Nevertheless, the ultimate effects of commercial thinning on even-aged redwood stands are not well known. With a light thinning, sprouting is low and less vigorous and generally will not develop as a significant understory. On the other hand, a thinning that greatly opens the canopy will generally result in vigorous sprouting, which should then develop as a younger age class. Successive thinning of the larger trees in a stand ("thinning from above") would then likely result in a change to an uneven-age structure (Helms 1995).

### *Uneven Age Systems: Single-Tree Selection*

Uneven-age systems can involve removal of individual trees or groups of trees. The uneven-age single-tree selection system seeks to maintain all age classes and a multilayered canopy, along with a constant supply of wood from year to year over a smaller area than possible with even-age management. At each entry, trees are removed within each diameter class to retain a target distribution. Harvest of older trees is compensated for by growth of young trees, enhanced by opening the canopy. Often all trees above some diameter, perhaps 1 m dbh, are removed. The single-tree selection system is based on the concept of self-thinning; that is, a certain number of small trees die because of shading and competition and a certain amount of regeneration occurs under the closed canopy. Because it is moderately shade tolerant, however, redwood does not self-thin like many other tree species. Small redwoods can persist in low-light situations, but the growth of individuals is less vigorous than under more open-canopy conditions.

In single-tree selection, stands are entered and trees are removed periodically, generally every five to twenty years. Factors such as economics, residual basal area, and growth rate need to be considered when determining the appropriate return interval. Frequent entries will result in greater soil compaction and residual stand damage, whereas return intervals that are too long are likely to result in holding costs of the residual growing stock (i.e., forgone revenue). A minimum volume to remove to offset logging and roading costs was estimated as 5,000 board-feet per acre (50 $m^3$/ha) in two studies in the redwood region (Adams 1980; Kennedy 1983).

Because small redwood trees survive and persist within dosed stands, at each entry within a single-tree selection system numerous small trees need to be cut and removed to maintain the target diameter distribution. This practice adds considerable expense to the logging process compared to group selection or even-age systems (Kennedy 1983). In addition, Jacobs (1987) found that because redwood is unable to reproduce by seed under dense forest canopies because of low light and increased probabilities of infection by damping-off fungi, a light selection cut will favor the regeneration of grand fir and western hemlock over redwood.

At Jackson Demonstration State Forest, clusters of trees are removed as an approach to selection management. This technique is intermediate between single-tree selection and group selection systems. The groups of trees removed are usually clusters of sprouts growing around stumps. This practice has the benefit of minimizing the problems of felling and yarding trees; in addition, it opens the stand more, aiding the establishment of young redwoods. Such an approach eliminates some of the problems associated with classic single-tree selection management in redwood forests.

### *Uneven-Age Systems: Group Selection*

The group selection system is similar to even-age silviculture, except that the clear-cut areas are small, usually 0.04-1.2 ha. At each entry, several small groups of trees are removed and regenerated, whereas the remainder of the stand might receive a commercial thin. The area to be included in the group cuts at each entry is computed by multiplying the total stand area by the intended return interval and dividing by the intended rotation length. Biological and economic considerations influence the area selected. No definitive research has been conducted in the redwood region to establish optimal group sizes for this method.

Several recent studies have examined the growth and yield of second-growth stands under uneven-age silviculture (Adams et al. 1996; Helms and Hipkin 1996; Piirto et al. 1996). In a preliminary analysis, Helms and Hipkin (1996) found no marked effects on tree growth from widely different selection systems. Adams et al. (1996) concluded that uniform single-tree selection lacked the ability to assure the rapid regeneration growth of redwood afforded by the group selection system.

### *Current Silviculture Practices o f Small-Forest Owners*

Most landowners with small-forest holdings in California are interested in maintaining aesthetics and wildlife habitat. Consequently, they use some type of "green-tree retention" cuts (i.e., heavy seed tree or shelterwood cuts) or some other selection system-uniform, group, or irregular. A common approach is to enter a 40-60-year-old forest that has developed after the original logging of the old growth and remove 40--65 percent of the volume. The stand is then planted with a mixture of tree species. The next entry, which involves cutting part of the overstory and the younger, second canopy layer, may occur in twenty to thirty years. Trees are again planted. This practice creates a three-storied stand that produces revenue and is aesthetically pleasing. Nevertheless, unless managed specifically for biological values, these stands can have low populations of some species, such as spotted owls, that are found in a natural, late-seral redwood forest (L. Diller, Simpson Timber Company, pers. comm.).

Some small-forestland owners apply small to medium-size clear-cuts or seed-tree cuts. The resulting stands usually grow into the low-biodiversity stem exclusion Successional stage and are then sequentially recut before biodiversity increases through natural stand structural changes (L. Diller, pets. comm.).

## The Current and Future Landscape

The traditional silvicultural systems reviewed above, along with the diverse land-ownership pattern and the variable responses of landowners to regulations, have shaped the landscape of the redwood region. Currently, some 93-95 percent of the redwood forest is second and third growth (L. Fox pers. comm.). These young to middle-aged forests are a mosaic of dense, stein-exclusion stands dominated by sprouting redwoods and some partial selection-cut forests and recently clear-cut forests in the early shrub-seedling stage. Redwood trees grow well in this environment because of their sprouting ability and rapid regeneration from seed in disturbed forests in contrast to their slow growth under the old-growth canopy. A small proportion of these young forests is dominated by early successsional tree species, such as red alder. Most of central Humboldt County between the only two old-growth reserves, the Headwaters Forest and Redwood National Park (a distance of approximately 35 miles), consists of this pattern.

The present pattern of young forests in irregular patches generally favors animal species that require early successional habitats to meet some or all of their life-history needs. These species include black-tailed deer, elk, black bear (in part), foxes, mountain lions (responding to deer), bobcats, various rodents, and raptors. The present mosaic is less suitable for species of plants and animals associated with late-sera] forest (Diaz and Bell 1997). Nevertheless, some of the older second-growth forest patches support populations of red tree vole, flying squirrel, and fisher (see chap. 5).

Even the northern spotted owl, which is generally dependent on old-growth forests throughout its range, appears to be persisting in the landscape mosaic of reforested clear-cuts and mature second-growth forests in the redwood region. This mosaic provides a mixture of prey reservoirs, forage areas, and roosting and nesting structures for the owl (O'Dell 1996). In 1993, the California Department of Fish and Game estimated a population of 4,450-8,500 northern spotted owls in California, with many of the owls found in managed second-growth redwood forests (Lucas 1998). The rapid growth rate of redwood trees, combined with the persistence of structural legacies from former old-growth stands in many second-growth forests, explains in large part the survival of spotted owls and some other old-growth associated animals in these forests (Noon and Murphy 1997). Another factor benefiting the owl is that one of its major prey species, the dusky-footed woodrat, thrives in the landscape mosaic created by recent forestry activities (Sakai and Noon 1993; Giusti 1999).

The suitability of the present landscape for many other species associated with old-growth redwood forests is unknown. It appears, however, that many canopy lichens, mosses, liverworts, fungi, terrestrial mollusks, insects, and other taxa characteristic of the old-growth redwood forest are not found, at least as viable populations, in the modified landscape. Species that rely on snags and downed coarse woody debris, such as many salamanders, are reduced in these forests (see chap. 5). The long-term effects on biodiversity of eliminating 95 percent of the old-growth redwood forests remain to be seen.

The landscape pattern of the redwood region is beginning to change again. In some areas near cities and along the public highways that transect the region, the human population is growing rapidly, principally through people moving into new subdivisions. This trend is expressed by an increase in buildings, roads, lawns, pastures, fences, domestic animals, and other artifacts of civilization. The average size of individual parcels of private forestland is declining in response to high inheritance and estate taxes, among other influences. Some of the large timber companies are selling parcels of their large forest ownerships adjacent to newly suburbanized areas because of conflicts with the public over silvicultural practices. A major increase in the human population in the redwood region is expected within the next twenty years, which inevitably will lead to more land in rural residential uses. These trends will probably increase fragmentation of the forest, with corresponding effects on fragmentation-sensitive species.

Most of the new forest owners say their priorities are aesthetics, wildlife, investment values, and the like; fewer forest owners have timber production as their primary goal. Almost half, however, think they will harvest some timber from their land in the next decade. These owners generally do not belong to forestry organizations or read forestry magazines. Hence, they seldom are knowledgeable about forestry or know where to look for advice on forest management. The result is often lost opportunities for the landowner and declines in the health and sustainability of the redwood forest (Sampson 1998).

## Future Silvicultural Management of Private Forestlands

In the late 1970s, forestry practices began to change dramatically in the redwood region. Increasingly, the public regarded clear-cuts as ugly and environmentally destructive. A developing environmental consciousness among a large and politically effective segment of the population led to pressure on forest managers to be more "ecological." For example, in 1979 the citizens of the city of Arcata passed an initiative to manage their forests for utilization of the resources in accordance with the principles of ecological forestry and perpetual sustained yield for both consumptive and nonconsumptive uses.

Soon, new organizations were founded to promote sustainable forestry in northwest California. The Institute for Sustainable Forestry, a community-based organization, was founded in 1991 to promote stewardship forestry through education and demonstration, and has developed a program of certification and labeling of sustainably harvested forest products.

The Pacific Forest Trust was founded in 1993 to promote stewardship forestry on private forestlands. Their main objectives are to restore, enhance, and protect private, productive forestlands. The Trust serves as the coordinating body in the Pacific states for developing forest certification standards consistent with international Forest Stewardship Council standards and criteria. Working with several small-forest owners in the redwood region, the trust has the first paid-for, forest carbon-storage program in the United States. The management plan allows cutting of annual growth for economic benefit, while promoting structural and tree species diversity, overall biodiversity, clean air and water, recreation, aesthetics, and carbon storage. The trust also has developed conservation easements for numerous small-forest ownerships.

With the listing, under the federal Endangered Species Act, of the northern spotted owl in 1990, the marbled murrelet in 1992, and coho salmon of the central California Coast Evolutionarily Significant Unit (ESU) in 1996 as threatened species, the management of private, industrial forestlands has had to include provisions for their habitat requirements. Commercial harvesting practices intended to accelerate creation of late-seral habitat components have been developed by state and private land managers. Practices include retention of large trees and multistoried canopy structure, and creation and maintenance of streamside ecosystem structure and function. The following are some of the major new silvicultural approaches being applied in the redwood region.

### *Shifting Mosaic of Variable-Size Patch Cuts with Variable Thinnings*

Second-growth redwood-mixed conifer-hardwood forests in some landscapes are being managed by creating a shifting mosaic of variable patch sizes on a 100-200-year rotation. This type of silviculture attempts to mimic the natural stand dynamics that occurred in the primary forests of this region, which were characterized by a shifting pattern of relatively small patchy disturbances, such as the death of individual canopy trees or groups of trees, forming gaps of various sizes and shapes. These gaps provide resources for establishment of young trees in the understory and increased height growth of individuals in lower and mid-canopy positions (Spies 1997).

This management regime attempts to maintain a high photosynthetic surface to take full advantage of available light, water, and nutrients. This is done by maintaining a deep and irregular canopy composed of all the tree species normally found on the site. This practice seeks to maximize the amount of fixed carbon converted to stored carbohydrates (wood). The optimal age and size structure of the canopy trees for storage of carbon is determined by the point where the amount of $CO_2$ fixed and stored is equal to the amount of $CO_2$ given off in respiration.

When stands reach this optimum age, size structure, and species mixture, the stands are thinned by removing the trees with small crowns and cutting some dominant canopy trees to create a mosaic of variable-sized, open patches. Never is more than 90 percent of annual growth cut in a ten-year period. A natural mixture of tree species is planted, using local seed sources, or naturally regenerated in these patches. Some of the patches must have sufficient sunlight to allow growth of shade-intolerant species, such as sugar pine and Douglas-fir, as well as moderately shade-tolerant species, such as redwood.

As the trees in regeneration patches grow and their crowns fill out, thinnings are applied to forestall early canopy closure and the development of the stem-exclusion successional stage, which is low in biodiversity. These thinnings favor a diversity of overstory and understory plant species and development of snags and coarse wood debris. They also optimize the growth of some trees, maintain the dense, variable vertical canopy, and provide a sustained flow of wood products and revenue (Carey and Curtis 1996). Usually, because of the uncertainty of this silvicultural system, 20-40 percent of the landscape is retained in uncut reserves, including riparian zones, special wildlife habitats, and inoperable areas. An attempt is made to reduce road densities by recontouring entry roads and planting trees and other vegetation.

More than a thousand hectares of forest in the redwood region are being managed using this silvicultural system; some have been for at least twenty years. Several have been certified as being managed sustainably. Monitoring of operations to assure that they meet sustainability criteria has been limited, however. Populations of spotted owls, wood rats, red tree voles, flying squirrels, winter wrens, nesting great blue herons, and other species of interest have been monitored in some of these forests. The willow flycatcher has been found breeding in young stands planted with Douglas-fir (Anderson 1998). Fishers have been reported to use older second-growth forests, where small patch cuts and group selection cuts duplicate the natural windthrow and fire regimes of older forests (L. Diller, pers. comm.), which are characterized by a diversity of tree sizes and shapes, light gaps and associated understory vegetation, snags, fallen trees and limbs, and limbs close to the ground (Ruggiero et al. 994).

Mendocino Redwood Company, a new company that recently purchased 93,000 ha of Louisiana Pacific's redwood lands in Mendocino and Sonoma Counties, is in the process of developing a forest management plan based on principles of sustainable forestry. They will not cut old-growth trees, apply herbicides, or create clear-cuts. They intend to maintain the structural attributes of natural ecosystems on their managed stands, including a mixture of dominant, intermediate, and small trees. Large snags and downed logs will be maintained in each stand. The stands will be managed to create horizontal habitat heterogeneity, with canopy gaps, dense clumps of trees, and a variable understory. When stands are harvested for timber, varying quantities of biological legacies will be left to provide quick successional recovery of the ecosystem, including soil organisms, tree symbionts, and decomposers (Franklin 1995). Although this type of management for a complete redwood ecosystem currently has limited application and monitoring in the redwood forest, it is consistent with the paradigm for forest management suggested by many conservation biologists (Noss and Cooperrider 1994; Carey and Curtis 1996; Meffe and Carroll 1997).

### *Single-Tree Selection with Late-Seral Habitat Components*

The Pacific Lumber Company, which developed a Habitat Conservation Plan (HCP) and Sustained Yield Plan (SYP) pursuant to Section 10(a) of the U.S. Endangered Species Act, has proposed two late-seral selection regimes intended to provide late-seral habitat components and stream shading and buffering. The first regime targets a J-shaped distribution of tree diameters, maintaining trees up to 40" (1 m) dbh with a postharvest basal area of 240 sq ft (55 $m^2$). Stands would be entered no more often than every twenty years. The second late-seral regime is similar to the first, but seeks to maintain larger trees, up to 48" (1.2 m) dbh, and higher residual basal area, 300 sq ft (69 $m^2$). Stands must have at least 276 and 345 sq ft (63 and 79 $m^2$) of basal area, respectively, for the two regimes before entry and retain at least 20,000 board-feet per acre (200 $m^3$/ha) in volume. Pacific Lumber has proposed 30-foot (10 m) no-cut buffers adjacent to streams.

Approved by the U.S. Department of Interior just before this book went to press, Pacific Lumber's HCP/SYP was hotly contested. The streamside buffers are considered inadequate by many aquatic biologists who have reviewed the plan (see appendix 8.1 and chap. 6). Furthermore, Pacific Lumber defines as "late seral" and "old growth" redwood forests that most forest ecologists would call "young." The HCP/SYP defines late-seral forests as "made up of stands with overstory trees that on average are larger than generally 24" (0.6 m) and may have developed a multistoried structure. It occurs in stands as young as 40 years but more typically in stands about 50 to 60 years old and older" (Pacific Lumber Co., unpub.). By well-accepted criteria and definitions, however, redwood and Douglas-fir forests less than 100 years in age would be considered young forests, not late-seral (see chap. 4, box 4.1). Pacific Lumber's late-seral and old-growth management strategy will fail to maintain true late-seral and old-growth forest in the planning area (Noss, unpub. review of Pacific Lumber HCP/SYP).

Managers for the Jackson Demonstration State Forest (JDSF) have proposed several silvicultural prescriptions intended to maintain uneven-age stands with large trees. The goal of the regimes is to create multistoried stands dominated by large trees as soon as possible. For their upland all-aged, large-tree emphasis regime, the targeted residual stand condition is 23-46 $m^2$ of basal area in trees greater than 24" (0.6 m) DBH and 35-46 $m^2$ of basal area in trees less than 24" DBH, depending on site quality. The prescription also calls for retention of all snags and downed logs, depending on safety considerations.

In addition, JDSF managers have proposed two approaches to maintain late-seral components within water and lake protection zones (WLPZs). The first approach is similar to the upland all-aged, large-tree emphasis regime, but stipulates that at least 75 percent canopy closure will be maintained within 25 feet (8 m) of the stream, and at least 50 percent canopy closure beyond 25 feet. The second targets a J-shaped diameter distribution for trees less than 24" (0.6 m) DBH, while maintaining a uniform distribution and number of trees greater than 24" DBH. The managers also aim to maintain 75 percent canopy closure within 8 m of streams and 50 percent beyond.

Another example of single-tree selection, but with group selection applied in some areas, is provided by Big Creek Lumber (box 8.1). This company has

Box. 8.1. Big Creek Lumber

When it comes to logging redwood in California, there are few examples that people point to as exemplary, both economically and environmentally. But Big Creek Lumber, a family-owned timber grower, miller, and retailer, has won the admiration of a broad coalition. The company has become a leading example of local control that allows timber and residential landowners to coexist amicably.

Begun in the 1940s by the McCreary brothers, Big Creek now owns and operates 10,000 acres of the Santa Cruz Mountains, the Coast Range south of San Francisco. Their mill in Davenport, on the Pacific Coast north of Santa Cruz, uses. logs from these lands as well as logs from another 50,000 acres, what forester Mike Jani calls the Big Creek "client base." The entire timber supply is from private lands, and the mill saws up to 15 million board-feet (150,000 $m^3$) of timber per year.

Big Creek's "vertical integration" is one key to its success. Big Creek manages the forest from the soil to the market. Working with owners of parcels as small as one hundred acres, Big Creek's foresters prepare management plans for sustainable harvests well into the future. This cuts down on future paperwork, assures the landowners that their land is well cared for, and creates a log base for the mill. Big Creek can count on this supply, so they do not need to approach land with a liquidation philosophy; they know that their timber supply is. as predictable: as the growth of trees. Their retail outlet sells half of their total production and specializes in environmentally certified redwood lumber. The lands and foresters of Big ,a Creek have been certified by Scientific Certification Systems (SCS) under Forest Stewardship Council standards and guidelines to husband the lands owned by the company and also those of the client base.

(*continues*)

Box. 8.1 (*continued*)

It is interesting that Big Creek views their major block of production, those of the unconsolidated landowners, as "clients." In many ways, these lands are the vendors, those who keep the supply flowing for the mill. The landowners, however, look to Big Creek for environmental guidance, forest management, and regulatory compliance as well, so the lands are both suppliers and clients. Jani says the process works because their client base has a like-minded philosophy about such things as stream protection, growing stands for old-growth characteristics, and a 100-year rotation.

Big Creek has chosen not to expand beyond its production capacity. Its expansion into new markets has allowed the business to grow and mature, increasing the company's profitability without increasing its production or its client base's cut. The selection management required in Santa Cruz County has increased overall. volumes in the area, and logs that Big Creek cannot use travel hours and hundreds of miles to more hungry mills.

Big Creeks management is most often single-tree selection. As required in Santa, Cruz County, no clearing in a dominantly redwood stand can exceed one-half acre. Cut trees must have leave trees within 75 ft (25 m), and at least half of the trees in the stand greater than 12" (0.3 m) dbh must be retained. There are a few exceptions to this approach. In a few Douglas-fir stands, Big Creek conducts group selection, with clearings up to 1 ha: in unentered old growth, They cut lightly or not at all (remnant old-growth trees, however, may be cut, which has engendered some controversy).

Big Creek is proud of their habitat work. Near streams, they maintain greater than 75 percent canopy retention, and areas with marbled murrelet habitat are not entered during the breeding season; critical habitat trees are retained. The company conducts a comprehensive murrelet survey. Using the results of this survey, they will attempt to selectively harvest some unoccupied stands with old-growth characteristics. Big Creek is also interested in marketing its environmental resources,. through easements and sale of fee lands, as lands that can be removed from their timber base.

Big Creek recently placed 146 ha into a permanent conservation easement. The property contains significant stands of rare old-growth and mature second-growth redwoods. Situated near Butano State Park, Año Nuevo State Reserve, Big Basin Redwoods State Park, and the West Waddell Creek State Wilderness Area, this forest is an integral part of a network of protected land in San Mateo County. Butano Creek, home to steelhead trout, is protected through restrictions on harvest to reduce sedimentation. Forest management will be focused on maintaining and enhancing old-growth habitat required by threatened and endangered species, such as the marbled murrelet.

Invasive exotic plants are a constant concern in Big Creek's management program. Pampas grass and French broom are controlled with an annual mowing program, without herbicides. Jani says the key to control of these plants is keeping the canopy intact, and their cutting methods are designed to limit the expansion of these aggressive, nonnative plants.

Resistance from environmentalists is a common deterrent to logging in the Santa Cruz Mountains, but generally good relations with the community, based on a consistent track record, has kept Big Creek in the woods rather than the courtroom. They regard their certification by SCS as a demonstration to the community of their good intentions and environmental stewardship.

Big Creek views itself as an important player in the future of Santa Cruz County and a model for the continuous production of redwoods in an increasing urban and restrictive environment. Pressure to build more private residences in the woods, to keep timber operations further segregated from residences, and to reduce timber management options are unrelenting in the area, the forest just over the hill from Silicon Valley. Big Creek works with the county Board of Supervisors to reduce the effects of urbanization and to make logging rules more accommodating to the people of the community.

achieved the advantage of having its operations certified as environmentally responsible.

### *Short-Rotation Plantations with Variable Green-Tree Retention*

The Simpson Timber Company manages even-aged plantations on short rotations. In an effort to protect and enhance spotted owl habitat as part of their HCP, managers are applying low to medium levels of green-tree retention. This system includes maintaining intact patches of trees greater than 0.2 ha in clear-cuts, enhanced WLPZ protection, and scattered groups of 10 to 12 trees and snags depending on site-specific conditions (Hibbard 1996).

The variable green-tree retention system has been applied to second-growth stands that developed after the cutting of the primary forests. These stands, which contain remnant snags, cull trees, and downed coarse woody debris, are clear-cut at about fifty years of age, with most of the merchantable residual logs and snags removed. Some snags and downed logs are left for wildlife, as well as a variable number of second-growth trees of all species left for wildlife and streamside protection. Today, this retention varies widely from one clump of five trees per 2 ha to 25 percent of the volume left as streamside cover and irregular clumps of trees in each clear-cut. Clumps of trees to be retained are selected by a wildlife biologist. Slash and second-growth understory vegetation are not burned. Two-year-old bareroot seedlings of redwood and Douglas-fir are planted in the untreated slash and ground vegetation. The seedlings are protected from deer browsing by vexar tubes. If early successional trees and shrubs, such as red alder, tanoak, blue blossom, and manzanita, begin to outcompete the planted conifers, the competing vegetation is treated with a basally sprayed herbicide. Some of these stands may later be precommercially and commercially thinned to optimize stand volume and individual tree growth.

### *Structural Retention Cuts*

Structural retention silvicultural systems are being used by several consulting foresters and one large timber company in redwood forests. In 30-100-year-old, second-growth redwood-mixed conifer-hardwood forests, the stands are entered once every ten years to remove 30-40 percent of the volume, leaving the best-formed trees regardless of spacing (J. Able, forestry consultant, pers. comm.). It is assumed (not proven) that the volume removed will be replaced on the remaining leave trees within a ten-year period. The stands are always kept in a mixture of tree species.

This retention system is a "thinning from below," or natural thinning method, which works well for redwood and associated tree species. Trees with less than 30 percent live crown are thinned out, leaving redwoods with greater than 30 .percent live crown more light and growing space. Redwood trees respond by filling out their crowns with greater growth of branches and more needles on each branch; this creates a much greater photosynthetic surface with less respiration cost, thus increasing growth. Furthermore, most of the growth is in larger trees, which increases their economic value. This type of partial cut eliminates heavy blowdown, excessive damage from bears and other animals, and thinning "shock" to the leave trees.

Growth in stands harvested by partial-retention cuts shows no signs of slowing (D. Thornburgh, pers. obs.). Eventually, these stands must be regenerated by a heavier cut or other disturbance, but can probably produce wood profitably and continue growing for another 100 to 200 years. These stands, which have a dense upper canopy but very little understory of shrubs or small trees, appear very similar to a natural, self-thinned, upper-slope old-growth forest with frequent understory burns. A disadvantage is that this type of silviculture requires frequent entries with logging equipment (e.g., every ten years) and a high road density of 10-12 miles/square mile (6.25-7.42 $km/km^2$). Many of these stands seem to have low species diversity and lack spotted owls and understory mammals (D. Thornburgh, pers. obs.). Where managers retain old-growth "heritage" trees, as well as downed wood, snags, and other structures, biodiversity is higher (E Euphrat, pers. obs.).

### *Other Approaches*

Among the measures to enhance wildlife habitat in redwood forests is noncommercial stand manipulation to create wildlife habitat components. In many traditional silvicultural systems, as well as some alternative or "ecoforestry" systems, a major objective is to capture tree mortality-that is, to cut trees that would soon die naturally. This practice results in fewer snags and downed logs—structures that provide nesting and foraging habitat for numerous species of animals (see chap. 5)--within the managed forest. Large, dead wood also plays an essential role in stream ecosystems (see chap. 6)--for example, by helping to create pools and thereby improving habitat for salmon.

Because trees are not left to die in traditional managed forests, other strategies must be employed to provide crucial habitat components. Girdling of trees to create snags provides habitat for cavity-excavating birds; these cavities, in turn, are used by many other birds, mammals, and invertebrates. Snags ultimately fall, providing downed logs. Because redwood is resistant to fungi and other decomposers, girdling of associated species, such as Douglas-fir and grand fir, will produce snags usable by additional species. Little is known of the suitable density and size distribution of snags to leave for wildlife in the redwood region. Bingham and Sawyer (1988) found 957 $m^3$/ha or 200 t/ha of downed logs within an 80-ha area of upland old-growth redwood forest. Whether this volume is representative of all old-growth redwood stands is unknown, but it is comparable to that found in studies in old-growth Douglas-fir and western hemlock forests in coastal Oregon and Washington (Harmon et al. 1986; Graham and Cromack 1982).

### *Summary of New Silvicultural Practices*

All of the approaches reviewed above seek to leave more large trees and corresponding structures-live and dead-on the landscape than in traditional even-age silviculture. The precise amount and juxtaposition of leave areas (retained patches), leave (uncut) trees, and structures needed to sustain a healthy redwood forest are unknown. It will take time to understand fully the ultimate ecological effects of new silvicultural approaches, which underscores the need to treat these approaches as experimental (i.e., as adaptive management; see following section).

Throughout the redwood region, many forest owners and foresters are mov ing in the direction of sustainable forestry as outlined in the Montreal Process and the Santiago Agreement in 1995, which were signed by the U.S. govern ment (see *Journal of Forestry* 93[4]:18-21). The Santiago Agreement recognized that "forests are essential to the long-term well-being of local populations, national economies, and the earth's biosphere as a whole" and endorsed six criteria of sustainable forestry: (1) conservation of biological diversity; (2) maintenance of productive capacity of forest ecosystems; (3) maintenance of forest ecosystem health and vitality; (4) conservation and maintenance of soil and water resources; (5) maintenance of forest contribution to global carbon cycles; and (6) maintenance and enhancement of long-term multiple socioeconomic benefits to meet the needs of societies.

Large and small timber companies alike are taking criteria such as these into consideration in their operations. They are attempting to manage their lands not only for timber but for biodiversity, clean water and air, carbon storage, alternative forest products, recreation, and aesthetics. Large timber companies in the region have expanded their wildlife and fisheries staff and are preparing HCPs and other broad-spectrum plans. These plans remain controversial and may ultimately fail to meet the criteria for ecological sustainability, where the natural structure, function, and composition of the forest is sustained in perpetuity (Noss 1990, 1998; Christensen et al. 1996). Nevertheless, if they can be strengthened and made adaptable to changing conditions (i.e., they are not constrained by biologically unrealistic "no surprises" clauses; Noss et al. 1997) they will have a far better chance of meeting biological objectives than traditional silviculture.

## Adaptive Management and Monitoring

To move silviculture toward ecological sustainability requires additional and continued changes in current practices. Among the changes that forest ecologists agree are necessary, long rotations, structural retention, and structural restoration stand out as particularly well supported by current theory and empirical data (Kohm and Franklin 1997). Nevertheless, many questions remain unanswered: How long should rotations be? Precisely what kind of structure should be retained-for example, what size and decay classes of logs and in what proportions? How should leave trees be spaced-separately, in clumps, or in a mixture of patterns? How many are needed? For how long or over how many rotations should leave trees be retained? What specific silvicultural practices will best restore second-growth forests or plantations to natural structure? How will populations of sensitive species respond to the lag time between the initiation of restoration and achievement of the desired conditions?

These questions have no general answers. For the redwood forests, different plant associations, site conditions, stand histories, landscape contexts, and other factors will call for different practices. Faced with the inevitable uncertainties about the effects of alternative silvicultural regimes, the best that forest managers can do is to use their ecological judgment as a starting point and then apply adaptive management-learn by doing-in an intelligent, reasonably controlled, responsive way (Honing 1978; Walters 1986; Noss and Cooperrider 1994).

Adaptive management requires, first, humility-the admission by forest managers that they do not have all the answers and that everything they do is an experiment with an uncertain outcome. In practice, "management" and "humility" have been countervailing concepts, and this needs to change. Beyond humility, adaptive management requires a commitment of scientific oversight to forest management in perpetuity. Information coming in from on-site monitoring (e.g., on population trends of target species, responses of a stand to harvests and to management treatments such as prescribed burning) is combined with remote sensing information showing the condition of the broader landscape, along with data from relevant research projects, to inform and revise site-specific and regional forest management plans.

Adaptive management relies on measurable indicators that correspond to the elements of forest biodiversity, health, and sustainability that forest managers--and society generally-find valuable. Such broad values cannot be measured directly. Only by measuring indicators can managers gauge the effects of their management treatments. Although few indicators have been adequately tested or validated, many reasonable ones have been suggested. A commonsense approach is to develop indicators that correspond to trends of interest in a particular forest landscape (table 8.1). These indicators can be measured to track

Table 8.1. Indicators That Might Be Used to Monitor Recovery of Redwood Forests.

| *Desired Trend* | *Indicators* | *Scale and Type of Measurement* |
|---|---|---|
| Shift from younger to older age classes of trees; recovery of old-growth stands and old individual trees | Rotation period of stand-replacing disturbances (natural and human-caused); diameter and age class distributions of surviving trees in stand and trees removed from stand; mean and range of tree ages within defined seial stages across landscape; diversity of tree ages or diameters in stand; area of landscape occupied by old growth and other seral stages; amount of late-successional forest habitat in all patches and per patch | Landscape (remote sensing) and stand (direct measurements) |
| Shift from simplified secondary forests and plantations to structurally complex, all-aged natural forests | Abundance and density of key structural features (e.g., snags and downed logs in various size and decay classes); spatial dispersion of structural elements within stand; physiognomy, including foliage density and layering (profiles), canopy openness, and horizontal patchiness of profile types; percentage of stand in gaps of various sizes and ages since formation; diameter and age class distributions of surviving trees in stand and trees removed from stand; diversity of tree ages or diameters in stand; abundance of species dependent on particular structural features | Direct stand-level measurements for most indicators; remote sensing for some (e.g., gaps) |

(*continues*)

Table 8.1. (*continued*)

| *Desired Trend* | *Indicators* | *Scale and Type of Measurement* |
|---|---|---|
| Shift from small, isolated patches of forest to large blocks of continuous forest | Forest patch size frequency distribution for each seral stage and community type and across all stages and types; size frequency distribution of late-successional forest interior patches (minus defined edge zone, e.g., 100-200 m); fractal dimension (a measure of boundary length and complexity); patch shape indices (e.g., deviation from roundness); patch density; fragmentation indices (e.g., from FRAGSTATS software); relative abundance and demographic characteristics of species requiring large patches of forest | Landscape-scale measurements using remote sensing (with ground-truthing); surveys of area-dependent species |
| Separate, isolated patches of forest replaced by continuous or connected forest | Patch density; fragmentation and connectivity indices; interpatch distance (mean, median, range) for various patch types; juxtaposition measures (percentage of area within a defined distance from patch occupied by different habitat types, length of patch border adjacent to different habitat types); structural contrast (magnitude of difference between adjacent habitats, measured for various structural attributes); presence of habitat corridors or other movement routes for fragmentation-sensitive species; relative abundance and demographic characteristics of species with poor dispersal abilities or otherwise isolation-sensitive | Landscape-scale measurements using remote sensing (with ground-truthing); surveys of isolation-sensitive species |
| Recovery of natural fire cycles and other aspects of the natural disturbance regime | Frequency, return interval, intensity, timing (seasonality or periodicity), patch size (areal extent), predictability, variability, and other characteristics of fires and disturbances; patch size frequency distribution for each seral stage and community type; abundance and density of | Landscape (remote sensing) and stand-level measurements; surveys of disturbance-sensitive species |

| *Desired Trend* | *Indicators* | *Scale and Type of Measurement* |
|---|---|---|
| | key structural features (e.g., snags and down logs in various size and decay classes); physiognomy, including foliage density and layering (profiles), canopy openness, and horizontal patchiness of profile types; percentage of stand in gaps of various sizes and ages since formation; relative abundance and demographic characteristics of species sensitive (either positively or negatively) to fire and other kinds of disturbance | |
| Reduction of road networks and associated impacts | Road density (mi/ $mi^2$ or $km/km^2$) for different classes of road and all road classes combined; percentage of landscape in roadless area (for different size thresholds, e.g., 1,000 ha and above, 5,000 ha and above); miles or kilometers of roads constructed, reconstructed, and closed (seasonally and permanently) each decade; amount of roadless area restored through permanent road closures and revegetation each decade | Landscape-scale measurements using remote sensing (with ground-truthing); engineering data |
| Eradication or effective control of exotic species that invaded following road construction, site disturbance, and, dispersal by vehicles, other equipment, and humans | Ratio of exotic species to native species in community (species richness, cover, and biomass); invasion rates and pattern of spread of exotic species; demographic characteristics of particular exotic species and native species sensitive to predation or competition from exotics | Stand-level measurements; landscape-level measurements for exotic species tha can be sensed remotely |
| Decreased air pollution, including low-level ozone, acid fog, acid precipitation, and particulates | Direct measures of air and precipitation contents; biomass increment and other measures of tree productivity; input/output budgets of ions (as indicators of change in soil pH and nutrient status and of tree nutrition); level of direct damage to leaves and other tissues; status of pollution-sen sitive and pollution-tolerant species | Stand-level measurements; remote sensing of patterns of mortality and morbidity |

(*continues*

Table 8.1. (*continued*)

| *Desired Trend* | *Indicators* | *Scale and Type of Measurement* |
|---|---|---|
| Reduced negative impacts of recreational use of forests (hiking, hunting, fishing, camping, off-road vehicle use, etc.) | Access indicators (see roads indicators above; also density of airstrips, boat landings, other access points); size and proportion of area closed to human use; measures of erosion, ground-level vegetation density and condition; measures of exotic species invasion (see above); visitor days for various types of recreation; abundance and demographic characteristics of species sensitive to human harassment or simply human presence; visitor attitudes | Stand and landscape measurements; surveys of sensitive species and visitor attitudes |

*Note:* These are only examples of many potential indicators for monitoring and assessing the biodiversity and ecological integrity of forests.
*Source:* Adapted from Noss (1999).

the movement of particular stands and their components in the desired direction of ecological recovery. Different treatments can be compared with each other according to the response of indicators within each treatment.

The indicators to be measured in a particular forest must be narrowed considerably from the expansive list in table 8.1. Criteria for selecting indicators appropriate in a given case include (1) a validated relationship of the indicator to the phenomenon of interest, (2) convenience and cost-effectiveness of the indicator for repeated measurement, (3) ability of the indicator to provide an early warning of change or trouble ahead, and (4) ability of an indicator to distinguish changes caused by human activity from "natural" changes (Noss 1990). Although funding and staffing limitations will restrict the number of indicators that can be measured, relying on one or a very few indicators is precarious. Forest managers should try to generate reasonable hypotheses about the controlling factors that maintain the communities and species of concern, based on available empirical data and theory, and select indicators with verified or highly probable relationships to those factors. Indicators should be validated periodically through focused research that quantifies and verifies their relationships to ecological factors of interest.

Forest management and restoration should not be overly prescriptive, in the sense of aiming for a well-defined, desired future condition. Rather, adaptive management progresses by measuring the responses of indicators carefully, relating those responses to the particular management practices that produced them, and continually guiding forests in the desired direction through adjustment of management. "Knowing when we get there" is elusive because managers will never understand exactly what determines forest health and integrity nor will they be able to separate definitively human impacts on forests from the vagaries of nature (Noss 1999). The more carefully managers track the responses of forest ecosystems to alternative management practices, however, the more will be learned from these experiments. If this knowledge is combined with a true concern for the redwood forest and its many inhabitants, the forest ecosystem will be conserved.

## Appendix 8.I. California Forest Management and Aquatic/Riparian Ecosystems in the Redwoods

The California Forest Practices Act governs the most significant resource management activities on redwood landscapes in California: it determines what and where various forestry methods are permitted. These practices can have profound effects on the aquatic and riparian ecosystems of the redwood region (fig. 8.1; see chap. 6). Touted by some as the most stringent forestry rules anywhere, the regulations now appear inadequate to protect and maintain the natural structure and function of aquatic/riparian ecosystems. In 1997, for example, the California Department of Forestry (CDF) declared five redwood region watersheds "cumulatively impacted."

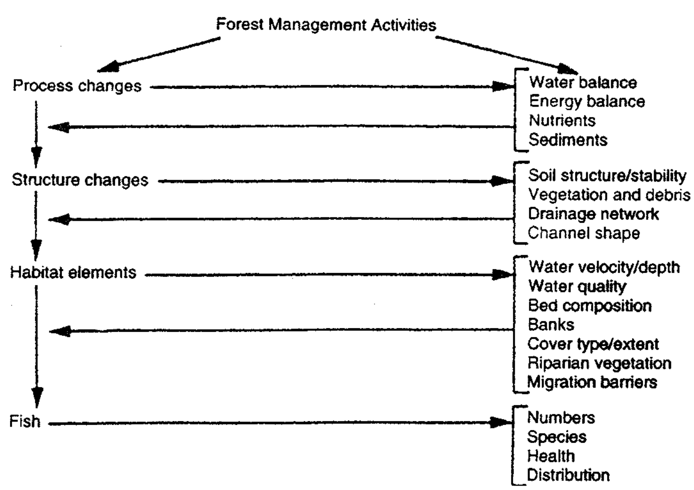


Figure 8.1. Linkages between timber management and biotic productivity. From Chamberlin et al. (1991).

The California forest practice rules were designed for the purpose of maximizing timber harvests while fulfilling minimal requirements for "consideration to" the public-trust resources of fish, wildlife, and water quality. One serious problem is the system of stream classifications used to determine allowable forestry practices adjacent to stream channels (class I = fish-bearing, class II = supports aquatic life, class III = does not support aquatic life). Basing management prescriptions on where fish occur reflects a bias for game fish over other aquatic life-forms and the integrity of the ecosystem as a whole (see chap. 6). Streams are a continuum (Vannote et al. 1980); what happens at the top of a watershed or catchment basin flows down through the system, influencing ecological processes and biotic interactions from the headwaters to the river mouth. Conditions in upstream channels determine the conditions in downstream channels. Ironically, the focus on where fish dwell ignores much of the ecosystem that supports and sustains them; consequently, not even fish are well protected by these regulations.

The timber industry, the California Board of Forestry (which oversees the timber industry), and the CDF have been slow to acknowledge the adverse effects of timber harvesting under current forestry rules (cf. Bella 1997). The nine members of the Board of Forestry are appointed by the governor, but must include four representatives of the timber industry. The denial of adverse influence of forest practices on riparian/aquatic ecosystems is sustained by the political leverage of the industry and its influence on local and state governments, despite scientific studies demonstrating negative effects of large clear-cuts and site conversions, poorly designed roads, harvesting on overly steep slopes, poorly designed stream crossings, and inadequate riparian protections (Meehan 1991; NRC 1996; Spence et al 1996; Stouder et al. 1997).

The following examples illustrate the inadequacy of current forestry rules for protecting riparian/aquatic systems. Under current rules, timber operators are responsible for maintaining roads for only three years postharvest and are required to erosion-proof only new or reconstructed roads. Yet the erosion of old logging roads has been shown by numerous studies to be a major preventable cause of siltation in many watercourses (Furniss et al. 1991; Harr and Nichols 1993; McGurk and Fong 1995). Under current rules, harvesting trees from the edges of the inner gorge of class II and III streams (those not supporting fish) is allowed. Nevertheless, these are the trees that contribute most to bank stability along headwater watercourses. This practice is analogous to pulling out the cornerstone of a building, and then when an earthquake occurs and the building collapses, citing the earthquake as the cause of the problem.

The current cultural/political climate surrounding forestry practices is exemplified by a recent situation in the Mattole watershed, an area with a substantial redwood component in its headwaters. A large portion of the Mattole watershed is listed as a Tier One Key Watershed under the President's Plan for the Forests of the Pacific Northwest (FEMAT 1993). This designation means the Mattole still retains populations of declining native species, such as coho and Chinook salmon, and therefore is a potential refugium for these threatened stocks. In the 1970s, the Board of Forestry was petitioned by citizens of the Mattole, who were concerned over cumulative adverse effects from timber harvesting (see MRC 1989). In response, the Board first proposed to set special timber-harvesting rules for the Mattole. Under threat of lawsuits from the timber industry, however, the Board decided instead to make a "sensitive watershed rule" whereby citizens could petition for special rules in a given watershed to address situations like that of the Mattole by presenting evidence of effects from past harvesting. Sensitive watersheds then must have some resource at risk that would not be protected under regular forest practice rules. The sensitive watershed rule went into effect in 1994.

In 1996, a petition was filed by local citizens nominating the Mattole under the new rule: The nomination was accompanied by copious evidence documenting increased sedimentation to tributary streams, lethal water temperatures, declining fisheries (coho and Chinook), declining amphibians, decreasing and ineffective amounts of late-seral forest (<8 percent of 1943 levels), erosion of old logging roads, widespread landsliding associated with past harvest activities, and other problems (Mattole Sensitive Watershed Group 1996). A panel to review this evidence was selected by the staff of the Board of Forestry in consultation with Board members. This panel was charged with evaluating the petition, assessing new evidence for and against it, and making a recommendation to the Board on the petition's merits. The sensitive status of the Mattole was acknowledged by five out of six state resources agencies that testified at public hearings. Only CDF denied the sensitive status of the watershed, despite an earlier letter from their own director identifying the Mattole as one of the most impaired watersheds in California. Three scientists on the review panel recommended acceptance of the nomination. Not surprising, however, given the balance of power that had been arranged by the Board, the vote was seven to six against the petition. With scientists kept in the minority, the Board of Forestry rejected the petition for sensitive watershed status.

To preserve and enhance the aquatic/riparian systems of the redwood region, more ecologically sensitive forest practice rules and an informed body to implement them are needed. A first step would be the appointment of a Board of Forestry representing the wide range of interests that depend on healthy and productive forest ecosystems. The Board also needs to develop a process to incorporate scientific evidence into its decision-making process (cf. Bella 1987). Such changes are necessary if California is to reverse the severe downward trends in fish and wildlife populations and water quality on commercial redwood timberlands and other heavily managed landscapes (Meehan 1991).

To sustain and promote riparian/aquatic ecosystem structures and functions

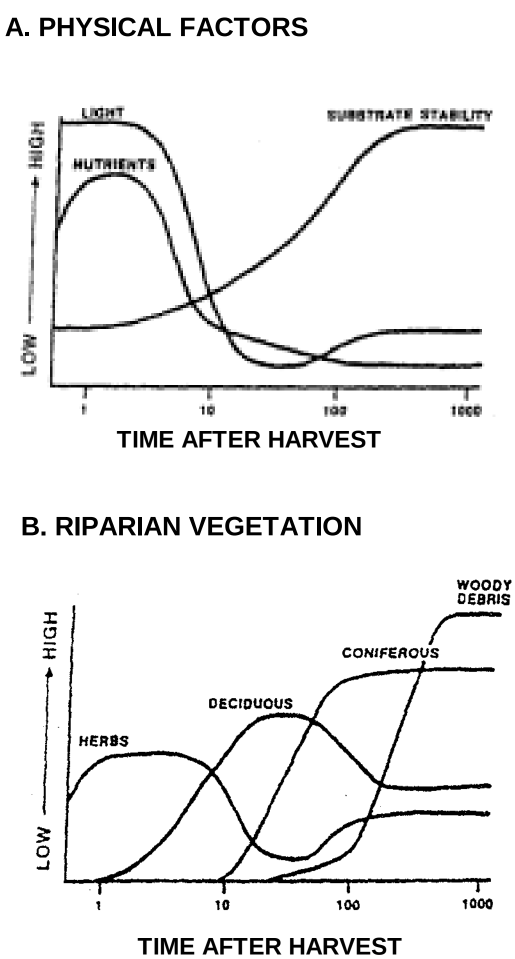


Figure 8.2. Recovery trajectories after timber harvesting of riparian structure in mature forest: *(A)* Physical factors; *(B)* Riparian vegetation. Time is expressed as years on a logarithmic scale. From Spence et al. (1996), after Gregory et al. (1987.)

before, during, and after timber harvest (fig. 8.2), revisions to the Forest Practice rules should (1) reduce excessive, human-accelerated watershed erosion and the amount of fine sediments entering stream systems by providing larger buffers on class II streams and buffers on class III streams where they are not currently required; (2) require larger buffers on all stream courses to moderate stream temperatures so streams can support native, cold-water-adapted fauna (fig. 8.3a) and to assure a future legacy of large trees that will eventually fall into stream channels, trapping and sorting streambed sediments and providing habitat diversity for stream fauna (fig. 8.3b); and (3) provide a constant source of nutrients from streamside forests from the headwaters downstream by buffering all classes of streams (fig. 8.3b).

Perhaps even more crucial than the protection of existing aquatic ecosystems

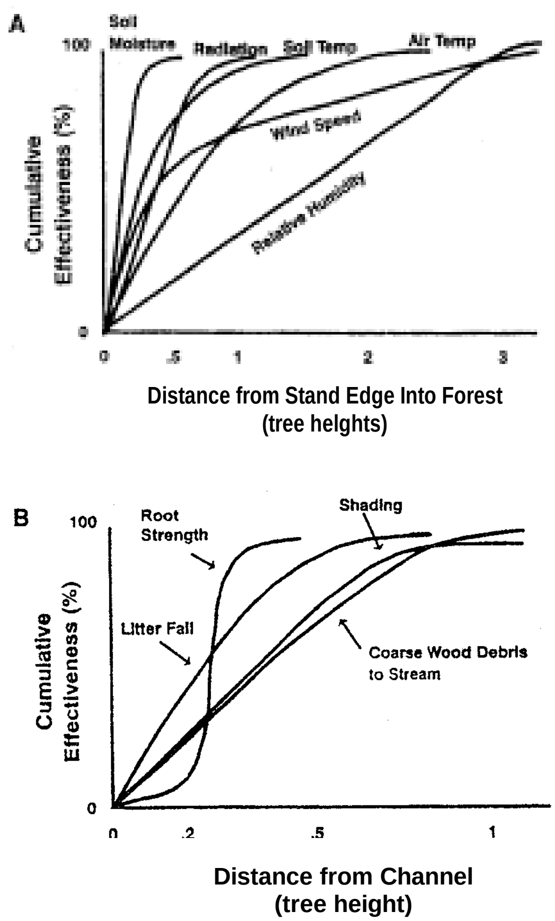


Figure 8.3. *(A)* The effects of riparian buffer width (distance expressed in site-potential tree heights) on microclimate. *(B)* The effects of riparian buffer width on four key ecological processes. From FEMAT (1993).

in the redwood region is the reestablishment of late-seral riparian communities. In streams where this is still possible (i.e., industrial forest lands), this condition will require new restrictions on timber harvest in the riparian zone to reestablish natural succession in these sensitive areas (fig. 8.2). As succession proceeds through the decades and centuries, the physical and chemical processes of streams will respond to changes in riparian form and function, and the aquatic community will be shaped by these evolving conditions.

Only a long-term solution, one that addresses both sustainability of ecosystems and human needs (table 8.2), can halt the ongoing decline in habitat quality and quantity in the riparian/aquatic component of the redwood ecosystem. Science does hold useful answers (e.g., Sedell et al. 1994, 1997; Reeves et al.

Table 8.2. Essential Components of Ecosystem Management.

| *Attribute* | *Description* |
|---|---|
| Sustainability | Ecosystem management entails managing in such a way as to ensure that opportunities and resources for future generations are not diminished. Sustainability should not be evaluated based on the delivery of specific goods and services, but rather on the maintenance of the ecosystem structures and processes necessary to provide those goods and services. |
| Goals | Ecosystem management requires clearly defined goals. These goals should not focus exclusively on individual commodities (e.g., board feet of timber, catch of fish, visitor days). They should be explicit in terms of desired future trajectories or behaviors for components and processes necessary for sustainability. |
| Sound ecological models and understanding | Ecosystem management is founded on sound ecological principles, emphasizing the role of ecosystem structures and processes. It must be based on the best science and models currently available. |
| Complexity and connectedness | Ecosystem management recognizes that ecological processes are connectedness complex and interwoven and that this complexity and connectedness may confer particular properties (e.g., stability, resistance, resilience) to ecosystems. |
| Recognition of dynamic nature of ecosystems | Ecosystem management recognizes that environmental change and biological evolution are inherent properties of ecosystems and that attempts to maintain particular ecosystem "states," rather than ecological capacities, are futile over the long term in a changing environment. |
| Context and scale | Ecosystem management acknowledges that ecosystem processes operate over a wide range of spatial and temporal scales and that their behavior (including their response to human perturbations) at a given location is strongly influenced by the surrounding landscape or sys tem and by the legacy of past events. |
| Humans as ecosystem components | Ecosystem management acknowledges that humans are components of ecosystems, as well as the source of most significant challenges to sustainability. Humans who are a part of ecosystems will, of necessity, define the future of those ecosystems. Thus, ecosystem management applied alone, without consideration of social and economic systems (and their sustainability), is insufficient to ensure resource sustainability. |
| Adaptability and accountability | Ecosystem management recognizes that current models and paradigms of ecosystem structure and function are provisional and subject to change. Acknowledging limits to scientific understanding and adapting to new information as it becomes available are central to successful ecosystem management. |

*Note:* Based on recommendations of Ecological Society of America. Christensen et al. (1996).

1995; NRC 1996; Spence et al. 1996; Stouder et al. 1997; Swanson et al. 1997; Naiman and Bilby 1998), but with current political and cultural climates, a major shift in how the public relates to ecosystems and their long-term sustainability must take place before broad support will exist to take advantage of this knowledge (Frissell et al. 1997). The challenge is to apply this knowledge now, in the face of political and cultural adversity, and to educate and persuade the doubters.

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