Conservation of biodiversity: a useful paradigm for forest ecosystem management

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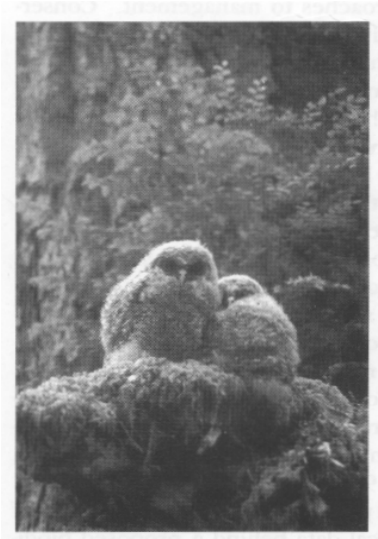
Conservation of biodiversity offers a paradigm for ecosystem management that incorporates ecological, social, and economic values. Careful application of the paradigm may help manage conflicts among interest groups.

The coniferous forests of the Western Hemlock Zone of western Oregon and western Washington are remarkable in the longevity and stature of their trees, long intervals between stand-replacing events, capacity to produce timber, diversity of life forms and species, and controversy over their management. The controversy is hardly new (Overton and Hunt 1974). But the current battle among those primarily interested in short-term commodity extraction, those interested in long-term support of rural communities through sustainable forestry, and those primarily interested in wildlife and recreation is unprecedented in its ecological, social, and economic impacts. We need a better approach to management of forest lands not reserved as natural areas, wildernesses, and parks. If we are to avoid past failures in conservation of natural resources (Ludwig et al. 1993), we must avoid the simplistic trap of viewing issues as timber versus wildlife as or commodity versus intangible values. We must seek reconciliation among the competitors who would use the forests.

Much of forest management over the past 50 years was based on commodity-oriented objectives and a less than adequate scientific evaluation of alternative management possibilities (Miller and Seidel 1990, Curtis



1995, Curtis and Carey 1996). Objectives often were narrowly focused, and non-timber values were not considered integral to management. Recent appreciation of other aspects of forest ecosystems has led to changes in management in the Pacific Northwest that, by and large, have been based on hypotheses unsupported by controlled experimenttation, carefully formulated theoretical constructs (management pathways), or even rigorous retrospective studies. Rather, these approaches have been based on individual professional experience, personal and philosophical attitudes, and the social

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and economic climate of the moment.

Ecosystem management has been proposed as a new paradigm for forest management, but as yet is poorly defined. Conservation of biodiversity is a related concept that differs from species-specific or commodity-specific management (Hunter 1990) and that provides an opportunity to develop reconciling, science-based approaches to management. Conservation of biodiversity is the "management of human interactions with the variety of life forms and ecosystems so as to maximize the benefits they provide today and maintain their potential to meet future generations' needs and aspirations" (Reid and Miller 1989:4). Reid and Miller (1989) suggest a definition of biodiversity that includes the building blocks of the biosphere (genes through ecosystems), the processes that shape these blocks, and the ecological and economic goods and services thus provided. Such a definition recognizes the human and economic aspects of ecosystem management that are essential for conflict resolution. If it is recognized that conservation of biodiversity is a foundation for sustainable forestry, artificial conflicts between conserving biodiversity and maintaining wood production disappear (Carey 1994*b*).

Our goal in this paper is to present a summary of theory and empirical data behind a proposed biodiversity pathway for forest management in the Pacific Northwest (Carey 1994*b*, Carey et al. 1996) along with a summary of new research on stand-development patterns and rotation ages for coastal Douglas-fir (*Pseudotsuga menziesii*; Curtis 1992, 1994, 1995; Curtis and Marshall 1993; Curtis and Carey 1996). We believe our approach can be used to provide: (1) forest products, (2) recreation and spiritual opportunities, (3) support for forest-dependent human communities, (4) habitat for most, if not all, forest wildlife, (5) healthy, resilient, forest ecosystems, (6) functional landscapes (Carey and Elliott 1994, Lippke 1994, Johnson 1995, Carey et al. 1996), and (7) reconciliation of alternative agendas for forest land management. Our approach has been used successfully in interagency mediation dealing with management of second-growth forests in federal adaptive management areas, late-successional reserves, and habitat conservation areas in Washington and Oregon. We believe this approach can be adapted, with modification, to other areas of the United States.

A biodiversity pathway for forest management

Empirical background

The first step in development was to conduct a retrospective survey of plant and vertebrate communities in young (40-80 yrs old), mature (80-200 yrs old), and old-growth forests (>250 yrs old) across the Western Hemlock Zone of the Pacific Northwest (Carey and Spies 1991). The fundamental question underlying the survey was whether there were plants or vertebrates associated with late stages of forest development that would be unlikely to persist in managed forests; and, if so, what were the features of late-seral forests with which these species were associated. A concept of ecological dependency was developed as an *a priori* basis for evaluating survey results (Carey 1984). Carey (1989) provided an overview of the results of the research program, and Ruggiero et al. (1991) presented detailed results. Some of the research suggested that there was regional variation in habitat relationships and that year-round resident vertebrates generally were more dependent on specific aspects of forest ecosystem development than were migratory species. For example, cavity-using birds (e.g., *Dryocopus pileatus*, *Parus rufescens*, *Sitta canadensis*, *Certhia americana*) were associated with old forests more than were neotropical migratory birds such as the hermit warbler (*Dendroica occidentalis*) and Nashville warbler (*Vermivora ruficapilla*; Carey et al. 1991). Subsequent research, therefore, focused on vertebrate communities closely tied to ecosystem function and productivity-forestfloor small mammal communities (Carey and Johnson 1995) and arboreal rodent communities (Carey 1991, 1995*b*,1996).

Concurrent work dealt with the ecology of the northern spotted owl (*Strix occidentalis caurina*). Forsman et al. (1984) documented a close association between the owl and old-growth Douglas-fir forest. Carey (1985) summarized published information on the spotted owl and other information needed for its management, based on a symposium for unpublished research (Gutierrez and Carey 1985). Methods of accelerating the process of forest development and restoring old-growth conditions through silviculture

were identified as important management needs. Subsequent research related to management pathways focused on owl-habitat relationships (Carey et al. 1990, 1992), owl-prey relationships (Forsman et al. 1991; Carey et al. 1992; Carey 1993, 1995*a*), prey ecology (Carey 1991, 1993, 1995*a*,*b;* Carey et al. 1992; Rosenberg and Anthony 1992; Carey and Johnson 1995, Carey 1996), and owl use of resources and space in landscape mosaics resulting from both natural and anthropogenic disturbances (Carey and Peeler 1995). Thomas et al. (1990) summarized extant research (published and unpublished) to formulate a conservation strategy for the spotted owl, which also called for development of innovative silvicultural approaches for habitat management.

Synthesis of data and theory into management pathways

In 1992, a group of scientists (biologists, ecologists, economists, an engineer, a sociologist, a silviculturist, and a biometrician) came together under the aegis of the Washington Forest Landscape Management Project, a congressionally mandated effort jointly managed by the U.S. Department of Agriculture Pacific Northwest Research Station and the Washington State Department of Natural Resources (Carey and Elliott 1994). Their mandate was to determine the feasibility, benefits, and costs of managing forests for multiple threatened species and forest products on a landscape scale, across ownerships and ownership types (federal, tribal, state, corporate, and private). As part of this effort, Carey (1994b) developed a biodiversity pathway for forest management on the western Olympic Peninsula: an integrated series of management actions designed for sustainable, joint production of forest commodities and ecological goods and services (from viable populations of wildlife to carbon sequestration). The pathway was based on research on biotic communities, niche theory (Whittaker et al. 1973, Hutchinson 1978, Begon 1986) and the practical implications of niche theory (Carey 1981, 1984, 1994a), forest ecosystem dynamics (Bormann and Likens 1979, Franklin et al. 1981, Harris 1984, Oliver and Larson 1990), and landscape ecology (Naumov 1963, Pavlovsky 1964, Odum 1971, O'Neill et al. 1986, Carey et al. 1992, Carey and Peeler 1995). A conceptual model of forest ecosystem development that allowed for divergent pathways was constructed. The biodiversity pathway was refined, further developed, and evaluated economically and ecologically in landscape-level simulations by the team (Carey et al. 1996).

A conceptual model of forest ecosystem development

The new model of forest ecosystem development defined 8 stages (Table 1). Previous models of stand development that had been used in forest management in the Pacific Northwest had 4-6 stages (Table 2). Oliver and Larson (1990) listed 4 stages of stand development: stand initiation, stem exclusion, understory reinitiation, and old growth. Brown (1985) described 6 stand conditions for analysis of wildlife-habitat relationships: grass-forb, shrub, open saplingpole, closed sapling-pole-small sawtimber, large sawtimber, and old growth. These apparently were derived from the traditional U.S. Forest Service timber-stand classes (Dilworth 1970). The Washington Department of Natural Resources Olympic Experimental State Forest developed 6 classes of vegetation structure for forest planning: open, closed A, closed B, understory, understory and layered, and old growth (unpubl. rep.). While these classifications proved useful in application, they lacked the detail needed to account for changes in composition, structure, and function of entire forest ecosystems in the Western Hemlock Zone of the Pacific Northwest. Particularly lacking were: (1) consideration of coarse woody debris and its diverse roles in the ecosystem, (2) recognition of the ecological crunch that competition among trees in closed-canopy forests exerts on an ecosystem, and (3) recognition of the tendency of conventional intensive timber-stand management (clearcutting, slash burning, herbicide application, precommercial thinning, and clearcutting at ages of 40-50 yrs) to simplify ecosystem composition and function (Table 2).

In retrospective studies of young, mature, and old-growth forests (Carey and Spies 1991), these 3 age classes of closed-canopy forests also proved overly reductionistic, even though site delimiters based on moisture (wet, mesic, dry) were used. Although numerous vertebrates increased in abundance with age (forest development), young stands resulting from natural disturbances often had sufficient biological legacies from old growth to provide adequate habitat for many species of wildlife (Ruggiero et al. 1991). Even stands resulting from clearcutting, given some biological legacies and variation in density of trees, were capable of supporting species associated with old forests and of maintaining the integrity of key vertebrate communities (Zarnowitz and Manuwal 1985, Carey 1995*b*, Carey and Johnson 1995). Spotted owls were observed foraging in second-growth stands (Carey et al. 1992, Carey and Peeler 1995) and marbled murrelets (*Brachyramphus marmoratus*) were found in "mature" stands (Carey et al. 1991). Other stands resulting from clearcutting and subsequent timber management were depauperate in species and presumably

Table 1. Eight hypothetical stages of forest ecosystem development in the Western Hemlock Zone of western Washington.

Stage	Code	Description
Ecosystem initiation	EIS	Death or removal of overstory trees by wildfire, windstorm, insects, disease, or timber harvesting leads to the establishment of a new plant community rapidly succeeded by other plant communities until trees dominate the ecosystem.
Competitive exclusion	CES	Trees fully occupy the site and compete with one another and other plants for light, water, nutrients, and space to the point where most other vegetation and many trees become suppressed and die.
Understory reinitiation	URS	Achievement of dominance by some trees and death (or harvest) of other trees leads to reduced competition that allows understory plants to become established.
Developed understory	DUS	Understories of forbs, ferns, shrubs, and trees have developed following death (or harvest) of some dominant canopy trees; there has been insufficient time for diversification of the plant community.
Botanically diverse	BDS	Organization and structure of the living plant community becomes complex with time and as the canopy opens further. Absence of coarse woody debris and other elements precludes a fully developed, complex biotic community.
Niche diversification	NDS	Organization and structure of the biotic community becomes complex with aggradation of coarse woody debris, litter, soil organic matter, and botanical diversity; foraging needs of all forest vertebrates are met.
Fully functional (managed)	FFS	Additional ecosystem development provides habitat elements of the necessary, large size and the time for development of function (interactions) to provide for life requirements of diverse vertebrates, invertebrates, fungi, and plants.
Old growth	OGS	Forest ecosystems after >250 years of development, uninfluenced by modern civilization, that have achieved elements of large stature, great diversity, and complex function.

Table 2. Three descriptions of forest development with stages and substages.

Stages of forest ecosystem development (Carey 1994*b*)	U.S. Forest Service (Brown 1985)	Olympic Experimental State Forest (age classes)
Ecosystem initiation grass–forb–shrub wildlife planting	Grass–forb Shrub Open sapling-pole	Open 0–5, 6–10, 11–15, and 16–20 yrs
Competitive exclusion biodiversity sapling-pole pole small sawlog large sawlog	Closed sapling-pole–sawtimber 1–21 inches dbh, >60% closure	Closed A, Closed B 16–20, 21–25, 26–30, 31–35, 36–40, 41–50, 51–60, 61–70, 71–75, 76–129 yrs
Understory reinitiation biodiversity sapling biodiversity small sawlog thinned large sawlog biodiversity small sawlog >10 yrs	none	Open 26–30 yrs Understory 36–40, 41–50, 51–55, 56–60 yrs
Developed understory thinned large sawlog >10 yrs biodiversity large sawlog	Large sawtimber >21 ins dbh, <100% closure, lacking CWD[a]	Understory and layered 61–65, 66–75, 76–129 yrs
Botanically diverse 90–160 yrs to develop, lasts 110 yrs, vegetatively diverse, lacks CWD	none	Old growth virgin stands, <250 yrs
Niche diversification CWD augmented, 50–60 yrs to develop, lasts 60 yrs	none	none
Fully functional ecosystem >110 yrs; CWD augmented	none	none
Old growth >250 yrs	Old growth >200 yrs	Old growth virgin or logged, >8 trees/ac 200 yrs

[a] CWD is coarse woody debris, used here to refer to fallen (or felled) trees, dead trees, and cavity trees.

in function, i.e., the interactions among ecosystem components that support diverse processes and species (Zarnowitz and Manuwal 1985; Carey et al. 1991, 1992; Carey 1995*a*,*b;* Carey and Johnson 1995).

Thus, Carey et al. (1996) suggested that additional categorization of the process of forest development would be desirable. It was apparent that forest ecosystems could follow different trajectories of development (even if the nominal plant community designation was the same), developing at different rates with different endpoints, depending on conditions at initial establishment, subsequent silvicultural practices, and subsequent local, natural perturbations. Thus, the classification scheme (Tables 1 and 2) was developed to include stages that reflected management for coarse woody debris and cavity-trees (niche diversification and fully functional) and stages that reflected simplifying effects of single-purpose management (developed understory and botanically diverse). For simulations of forest development, each stage was further divided into substages in 10-year increments (Table 3).

Some may find this new terminology awkward. Care must be exercised in its use to ensure good communication. Ecosystem initiation refers to the conditions and processes leading to the establishment or reestablishment of a forest ecosystem. Fully functional means that the forest serves all the functions (provides all the processes, goods, and services) that we have studied and that we are aware of; this term is used only in a managed-forest context. We don't know if forests in this stage are providing all the processes, species, goods, and services that natural old-growth forests provide. Old-growth forests are quite variable, differing in processes and functions. Finally, niche diversification may be the most awkward term. But, niche diversify-cation is a process that is integral to biodiversity management. A common understanding of community ecology is essential to ecosystem management (Carey 1981).

Traditional timber manage-ment with short rotations might follow a pathway of ecosystem initiation-competitive exclusion-ecosystem initiation, even with traditional thinnings. Long rotations could result in ecosystem initiation-competitive exclusion-understory reinitiation-ecosystem initiation, or even include developed understory and botanically diverse before final harvest. But without legacy management, such stands might never reach niche diversification and fully functional managed stages. Even second-growth stands set aside for preservation could spend long (> 100-yr) periods in competitive exclusion and could fail to diversify fully (i.e., they could stagnate or degenerate) or to develop into the botanically diverse stage. The completeness of the stand-replacing event (the degree to which biological legacies are lost) and time (total and proportional) spent in competitive exclusion determine the degree of ecosystem simplification and may be prime determinants of loss of resiliency to natural and anthropogenic disturbances. The biodiversity pathway capitalizes on added landscape diversity due to openings, minimizes or eliminates competitive exclusion, and rapidly moves the ecosystem into niche diversification, in as little as 50-70 years (Carey et al. 1996; Table 3).

Table 3. Development of *Tsuga heterophylla* zone forest on the Olympic Peninsula following clearcutting with no manipulation and protection (NMP), management for timber and fiber production (TFP), and management for biodiversity (BDP) (from Carey et al. 1996). Biodiversity thinnings are variable density (VD) and variable density with cavity-tree and coarse woody debris augmentation (CWD).

Decade (10 yrs)	NMP stage[a]	TFP stage[a]	TFP Treatment	BDP stage[a]	BDP treatment
1	EIS-1	EIS-1	none	EIS-1[b]	plant Douglas-fir
2	EIS-2	EIS-2	precommercial thin	URS-1	precommercial thin
3	CES-1	CES-3	commercial thin	URS-2	VD thin
4	CES-2	CES-6	clearcut	DUS-1	none
5	CES-3	EIS-1	none	DUS-2	CWD thin
6	CES-4	EIS-2	precommercial thin	NDS-1	none
7	CES-5	CES-3	commercial thin	NDS-2	CWD thin
8	CES-6	CES-6	clearcut	NDS-5	none
9	URS-1	EIS-1	none	NDS-6	none
10	URS-2	EIS-2	precommercial thin	FFS	none
11	DUS-1	CES-3	commercial thin	FFS	none or harvest
12	DUS-2	CES-6	none (or clearcut)	FFS	none or harvest
13	DUS-3	URS-1	commercial thin	FFS	harvest (or NMP)
14	DUS-4	URS-2	none	EIS-1	plant Douglas-fir
15	BDS-1	BDS-1	none (or clearcut)	URS-1	precommercial thin

[a] Stages are ecosystem initiation (EIS), competitive-exclusion (CES), understory reinitiation (URS), developed understory (DUS), botanically diverse (BDS), niche diversification (NDS), and fully functional (FFS).

[b] Includes biological legacies from the previous stand.

The managerial foundations of the biodiversity pathway

Five sequential steps formed the foundations for conservation of biodiversity in managed forests:

1. Conservation of biological legacies during harvest and regeneration by avoiding intensive site preparation and burning wherever these are not essential to establishment of regeneration or maintenance of forest health. Legacies include (a) soil organic matter, litter, and coarse woody debris, including snags; (b) mosses, lichens, forbs, ferns, shrubs, and live trees of the preceding forest; and (c) ectomycorrhizal fungi, which benefit from retention of coarse woody debris, ericaceous shrubs, and some living trees.
2. Planting Douglas-fir at wide spacing to insure representation of this species, while providing for natural or artificial regeneration of diverse canopy species such as western hemlock (*Tsuga beterophylla*), western redcedar (*Thuja plicata*), grand fir (*Abies grandis*), and western white pine (*Pinus monticola*). Concurrent regeneration of deciduous species such as red alder (*Alnus rubra*) and bigleaf maple (*Acer macrophyllum*) and evergreen hardwoods such as Pacific madrone (*Arbutus menziesii*) in limited amounts is desirable.
3. Minimizing area and time in the competitive exclusion stage (defined in Table 1) through precommercial thinning and commercial variable-density thinning.
4. Ensuring diversity and niche diversification in later stages through subsequent thinnings and coarse woody debris management.
5. Use of extended rotations (≥80-130 yrs vs. 40-50 yrs) on a significant part of the land base. Harvesting or regeneration systems could range from clearcutting to group selection or individual tree selection to none, depending on local conditions and the goals of the land manager.

Site preparation. Prescribed burning for site preparation is controversial. The need for routine prescribed burning as part of site preparation and the effects of prescribed burning on site productivity are not clear (see discussions in Hanley et al. 1989). For conservation of biodiversity, avoidance of prescribed burning is especially significant for forests dominated by western hemlock where intervals between catastrophic fires are long (>350 yrs), intervals between severe windstorms are short (<100 yrs), and accumulations of coarse woody debris and decaying organic matter have allowed for diversification of small mammal communities (Carey and Johnson 1995). In the Douglas-fir dominated forests of the southern Western Hemlock Zone, intervals between catastrophic wildfires are shorter (200-350 yrs), small-scale wildfires are more frequent (10-50 yrs), windstorms less important, and accumulation of organic matter on the forest floor is less than in the north (Spies and Franklin 1991). Thus forest dynamics and ecosystem development differ significantly within the same zone (Carey 1995*b*, Carey and Johnson 1995, Carey 1996).

Minimizing intensive site preparation, especially intensive burning, not only helps preserve biological legacies, but also reduces invasion by aggressive pioneer species such as red alder. Fewer fast-growing deciduous trees reduces the need for herbicides or other types of vegetation management that are often necessary to establish a new stand of conifers. Red alder, bigleaf maple, Pacific red elder (*Sambucus callicarpa*), and other deciduous trees, in low densities, are desirable components of coniferous forest ecosystems. Some sites, however, with dense shrub layers (often promoted by thinning) will require some vegetation control to secure establishment of conifers. After a new forest ecosystem has been established through planting and natural seeding, or in closed-canopy, second-growth stands, biodiversity thinnings are used to enhance, maintain, or restore diversity to the ecosystem.

Biodiversity thinnings. The proposed thinnings differ from those now in common use. Three kinds of thinning are suggested: (1) a precommercial thinning to forestall early canopy closure and favor diversity of overstory and understory plant species, (2) a variabledensity thinning, much heavier than conventional commercial thinning, to maintain tree growth, promote understory development, and provide a sustained flow of wood products and revenue, and (3) subsequent variable-density thinnings to add coarse woody debris to an ecosystem. In variable-density thinnings, ≥2 densities of retained trees are used to allow maximal canopy opening consistent with wind resistance and to promote heterogeneity in understory development at a spatial scale similar to that found in old-growth forests (Carey 1994*a*,*b*; Carey and Johnson 1995). For example, the first variable-density thinning could retain 309 trees/ha, and 185 trees/ha, in a 2:1 ratio on a 0.2-ha scale in a 30- to 50-year-old stand of 10to 50-cm dbh trees. Conventional commercial thinning for timber production might leave 355 trees/ha, evenly spaced. Actual target densities depend on diameter and crown sizes of the trees to be retained.

Natural canopy gaps that result from windthrow, disease, or natural variation in tree regeneration (Franklin et al. 1987) also are used to promote understory development (Carey 1994*a*, Fig. 1). Planting and

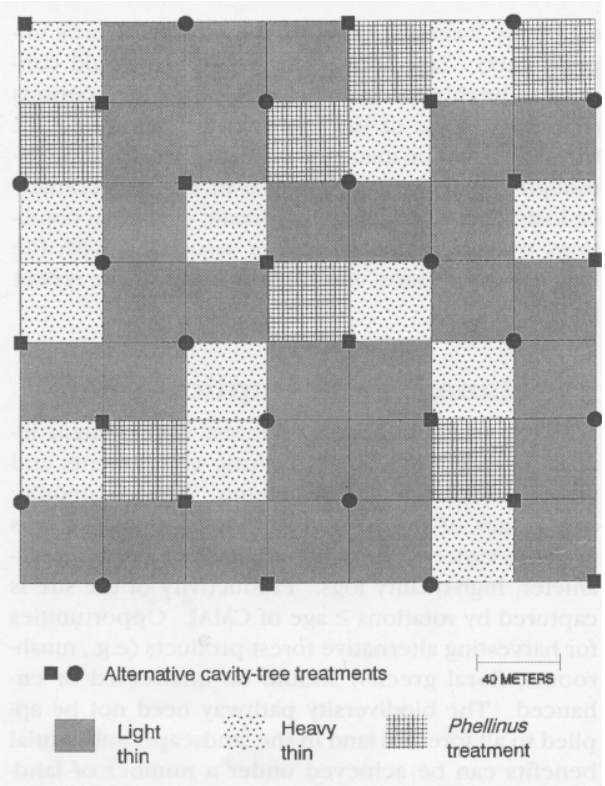

Fig. 1. An experimental application of variable-density thinning combined with cavity-tree augmentation in a stand of *Pseudotsuga menziessii* with residual coarse woody debris, Fort Lewis, Washington, 1993); the application includes capitalizing on existing *Phellinus weirrii* (root rot) pockets by felling low-vigor trees and underplanting with disease-resistant conifers (*Thuja plicata* and *Pinus monticola*) and Alnus rubra (from Carey 1994*a*).

and seeding in openings (e.g., with bigleaf maple, western hemlock, and western redcedar) can be used to provide architectural (tree form) and species diversity (Carey 1996). Root rot (*Phellinus weiriz*) is universal in the Pacific Northwest (W. Thies, Pacific Northwest Research Station, Corvallis, Oregon, pers. commun.) and cannot be ignored in management for biodiversity. Planting openings created by root rot with root-rot-resistant species aids in ecosystem recovery. Windthrow is common in western Washington and windthrown timber can be salvaged when damage is extensive, but should also be retained as coarse woody debris on the forest floor. Additional removal of trees may also be necessary to promote rapid ecosystem development.

At least 2 additional variable-density thinnings can be performed that: (1) emphasize leaving coarse woody debris to meet a target of 15% cover on the forest floor in northern Washington (Carey and Johnson 1995) and 8-10% cover in southern Oregon (A. Carey, unpubl. data), (2) provide the opportunity to create cavity trees (Carey and Gill 1983), (3) maintain development of a heterogeneous understory (Carey 1995*a*, *b*; Carey et al. 1992; Carey and Johnson 1995), and (4) provide revenues (and concomitant economic activity) from wood products (Lippke et al. 1996). Although less coarse woody debris is recommended for the southern Western Hemlock Zone than for the northern Western Hemlock Zone, it will be more difficult to provide because it should be of large diameter (>50-cm dbh when standing), whereas the coarse woody debris goals for the northern forests incorporate a mix of diameters (10- to 100-cm dbh). Large-diameter coarse woody debris cannot be provided in early thinnings; it must be provided in late thinnings or at harvest. Forests must develop for >100 years to achieve full function as later seral forests; thus long rotation ages are needed.

Rotation length. Part of the perceived biodiversity problem in the Pacific Northwest results from the unbalanced distribution of stand age classes (regionally and locally), and widespread adoption of short rotations by many owners. Rotations of 40-50 years are common on industrial and private ownerships, which usually seek to maximize discounted present net worth from timber production and are strongly influenced by current supply pressures. Public ownerships (which must consider other values in addition to investment return on timber) use rotations of 60-80 years or longer, depending on legislative mandates, political pressures, and philosophies of land-managing agencies. A shift to longer rotations on some of the land base would provide an ecologically more favorable distribution of stand ages and conditions, and in combination with the biodiversity pathway would increase the proportion of late-seral forests compared to the now common competitive-exclusion-stage forests.

The National Forest Management Act of 1976 (U.S. Dep. Agric. For. Serv. 1983) specifies that rotations on National Forest lands shall approximate the age at which mean annual increment in wood volume is maximized (culmination of mean annual increment [CMAI]). Recent research shows that maximum production of wood for harvesting (thinnings plus final harvest) occurs with rotations of 80 years (Curtis 1992, 1994, 1995; Curtis and Marshall 1993), and remains nearly constant for a considerable period of years.

Culmination of mean annual increment and rotation age

Age of CMAI is not a fixed, known age. It is influenced by site quality, species or species mix, and management. Early estimates for Douglas-fir in the

Pacific Northwest (McArdle et al. 1961) were underestimates, especially for thinned stands (Curtis 1992). More recent estimates of age of CMAI are >75-80 years (Curtis 1994, Curtis and Marshall 1993). A recent analysis of results of 17 long-term thinning experiments with stands now 60-117 years old found that CMAI had not yet been reached; periodic thinning delays CMAI (Curtis 1995). Short rotations (40-50 yrs) result in lower volume production/unit area than do long rotations (Curtis 1994). Because a CMAI curve is relatively flat in the vicinity of the age of culmination, there is a range of possible rotation ages beyond those in common use that will produce approximately the same long-term wood production (Curtis and Marshal 1993; Curtis 1994, 1995). The ages suggested in the biodiversity management pathway (≥80-130 yrs; Carey et al. 1996) are within the range of age of CMAI. With repeated thinnings, some vigorous stands could be grown to 200 years-Douglas-fir, western hemlock, and western redcedar are long-lived species. Thus, biodiversity thinnings and extended rotations should result in wood yields approximately equivalent to those under current management. Slight reductions may occur because deliberate efforts are made to thin in a manner that allows some of the sunlight, precipitation, and nutrients available to be captured by nonmerchantable understory vegetation, shade-tolerant trees, consumer organisms, and decomposer organisms.

There are economic costs as well as benefits associated with the biodiversity paradigm. The major cost is the reduction in present net value associated with extended rotations (Lippke et al. 1996). Such costs are partly or wholly offset by the increased value of large logs and increased production from the land, and the enhancement of associated nontimber values.

Regeneration systems

Biodiversity goals can also be enhanced by judicious use of alternative regeneration systems. Various species could be favored by planting and seeding or by regeneration activities. Coastal Northwest forests are generally best adapted to even-aged management, but this does not necessarily imply large clearcuts such as were common in the recent past or the currently popular green-tree retention. Promising systems include various forms of shelterwood (which retains a partial overstory until after regeneration establishment); small patch cuts of perhaps 2-5 acres each to create an uneven-aged forest composed of a mosaic of small even-aged stands; and retention of selected reserve trees through the second rotation to create 2-aged stands (Matthews 1989; Curtis unpubl. data). Late-seral, managed forests could continue to be thinned from below for extended periods (removing some of the in-growth of shade tolerant trees) or could be managed with group selection-although species such as Douglas-fir might eventually be lost. These systems avoid drastic change in conditions over large areas that are associated with the large clearcut, burn, and plant regimes of the recent past.

Management implications

This conceptual model of forest development incorporates living and dead biotic components and the effects of active management. The commodity advantages of the plan are obvious-a continuous flow of a variety of wood products, including large-diameter, high-quality logs. Productivity of the site is captured by rotations ≥ age of CMAI. Opportunities for harvesting alternative forest products (e.g., mushrooms, floral greens) should be unaffected or enhanced. The biodiversity pathway need not be applied to all forested land in the landscape; substantial benefits can be achieved under a number of landscape-management regimes (Carey et al. 1996). Similarly, it is not necessary to follow the biodiversity pathway to fruition in the fully functional stage; substantial benefits can be achieved from the niche diversification stage. As with any management approach, the exact application of the approach needs to be based on specific objectives and cost-benefit analyses.

The advantages to wildlife are also obvious. Examining and augmenting the wildlife-habitat relationships of 130 species of amphibians, reptiles, birds, and mammals described in Brown (1985), Ruggiero et al. (1991), and other published reports, Carey et al. (1996) found that, in western Washington, 1 species of reptile and 1 species of mammal were unique to the ecosystem initiation (regeneration) stage. No species were unique to competitive exclusion or other subsequent stages in a contemporary timber-fiber management regimes, and 14 species (2 amphibians and 12 birds) were unique to the upland forest resulting from the biodiversity management pathway (11 species were unique to rivers, streams, and streamsides). Forests actively managed for biodiversity could support 100% of the species occurring in western Washington, whereas timber management on a 50-year rotation at the landscape level could support a maximum of 87% and mode of 64% of the species potentially occurring in forests. The biodiversity pathway was better than traditional timber-fiber management for species as diverse as Roosevelt elk (*Cervus elaphus*) and spotted owls. Hansen et al. (1993) found similar results for western Oregon.

Thus, public land managers would benefit from adopting biodiversity management. Not only would long-term commodity output be maintained, but the health and function of the forest ecosystem would be protected and enhanced (Carey et al. 1996). Additional economic and ecologic benefits could accrue regionally and over time; these include diversified forest-based economies for rural communities and greater total employment over time, compared to traditional timber-fiber management (Lippke et al. 1996). Private land managers could receive similar benefits, but there would be real economic costs. Lippke et al. (1996) and Johnson (1995) discussed incentive programs that governments might institute to encourage private landowners to engage in biodiversity management. Benefits to private landowners would include regulatory certainty arising from habitat conservation planning.

Conclusion

We are not suggesting biodiversity management as a replacement scheme for reserves such as National Parks, Research Natural Areas, or other designated conservation areas or lands that might be managed intensively for timber or fiber production. This is a plan for extensive management and multiple-use lands. The principles and pathway can also be used to restore late-successional forests to areas where such forests are lacking, in a more timely manner than simple preservation of second-growth forests (Carey 1994*b*).

We do not expect biodiversity management to meet the needs or goals of all private landowners, even with active incentive programs; nor is it necessarily applicable to all public lands. The pathway requires a long-term commitment to intensive management at the landscape scale that incurs costs (e.g., planting, precommercial thinning, cavity-tree management, and maintenance of management infrastructure), as well as generating revenues. But its application to a portion of the land base can be an important component in a balanced approach to land management, and one that can go far to reduce the land-use conflicts and economic and social disruption experienced in recent years.

Finally, biodiversity management, the management pathways, and conclusions about rotation ages are indeed hypotheses that should be tested in management arenas and refined. One such test in Washington is now in its fifth year (Carey 1994*a*); another is in its third year (A. Carey, unpubl. data).

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