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ACTIVE AND PASSIVE FOREST MANAGEMENT FOR MULTIPLE VALUES

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ABSTRACT—Comparisons of natural and managed forests suggest that single-focus management of 2nd growth is unlikely to achieve broad conservation goals because *biocomplexity* is important to ecosystem capacity to produce useful goods and services. Biocomplexity includes species composition, the absolute and relative abundances of those species, and their arrangement in space (for example, trees and shrubs of various species, sizes, vigor, and decay states). Key to high biocomplexity is patchiness at the appropriate spatial scale (for example, 0.1 to 0.5 ha). Passive management (benign neglect) does not necessarily remedy whatever degradation might have occurred under past management or neglect (for example, lack of biological legacies, artificial homogeneity, loss of biodiversity, missing keystone species, presence of diseases, or increased vulnerability to disturbance). Furthermore, not all management is equal. Purposefully managing processes of forest development and landscape dynamics is more likely to be successful in maintaining ecosystem and landscape function (and adaptiveness) than just providing select structural elements in stands and select structural stages in landscapes, as is often suggested for conservation. Deliberate simplification of ecosystems (for example, even-aged, single-species plantations harvested every 15 to 40 y to maximize wood production) runs counter to conservation, even if rotations are extended slightly and conventional thinning is applied. Recent experiments support the importance of biocomplexity to soil organisms, vascular plants, fungi, invertebrates, birds, small mammals, and vertebrate predators. These studies suggest that various techniques used purposefully over time are more likely to be successful than any 1-time intervention, passive management, or traditional timber management. Biocomplexity is promoted by variable-retention harvest systems, planting and precommercial thinning for species diversity, variable-density thinning to create spatial heterogeneity and foster species diversity, managing decadence processes to provide cavity trees and coarse woody debris, and long to indefinite rotations. At the landscape scale, passive management (reserves and riparian corridors) that does not take into account restoration needs may be self-fulfilling prophecies of forest fragmentation and landscape dysfunction. Restoring landscape function entails restoring function to both 2nd growth and riparian areas. Intentional (integrated, holistic, and collaborative) systems management seems to offer the best hope for meeting diverse objectives for forests, including conservation of biodiversity, a sustained yield of forest products, and economic, social, and environmental sustainability.

Key words: forests, management, biodiversity, biocomplexity, values, sustainability

Societies demand much of their forests. When people were scarce and primeval forest abundant, forests were impediments to progress. Now people are abundant, forests are less pervasive, and most temperate forests are 2nd growth. As the pace of social evolution quickens, many look to natural forests for wholeness, stability, permanence, and other spiritual values beyond the traditional values of aesthetics, naturalness, wildness, clean air, clean water, subsistence hunting and gathering, open space, wildlife habitat, recreation, and wood and other commercial products. Millenarian forests of the Pacific Northwest (PNW) especially provide a "cathedral" that is spiritually evocative. Forested lands, however, continue to be converted to other uses even as the value of forests as providers of green space, clean water, clear air, and carbon sequestration are increasingly apparent (Best and Wayburn 2001). Furthermore, citizens in democracies increasingly demand social justice for people now (have vs. have-not groups) and in the future (leaving a good world to future generations) and for ecological justice for other species (Ray 1996; Shields and others 2002). Together, these demands are demands for sustainability, not only of our forests, but also our human communities, locally and across the globe. The highly valued old-growth forests are now mostly in reserves and parks, distant from people, and insufficient in area to provide various values in the amounts desired by people, including clean air, clean water, environmental cooling, open space, opportunity for outdoor recreation, wood and other forest products, and economic activity and employment associated with forest products near our villages, towns, and cities. Outside of reserves, many, if not most, of the values demanded by society, however, can be provided from abundant young forests, given proper management over the long term. Young forests with old-forest legacies may sustain biodiversity and may develop high biocomplexity and "naturalness" if left untouched (Carey, Kershner, and others 1999). High biocomplexity results from the interactions of species and the variety and arrangement of structural elements of the ecosystem in space at a spatial scale that produce emergent (synergistic) properties (the whole far surpasses the sum of the parts) such that diverse values can be produced at simultaneously high levels from the same ecosystem. Biocomplexity, especially diverse and abundant flowering plants, mushrooms and other fungal fruiting bodies, very large trees and their epiphytes, and the presence or signs of wildlife, does much to promote human experiences of wildness, naturalness, and spirituality (Wilbur 1995; Carey 2003c). But much 2nd growth, even within reserves, is low in biocomplexity (simple in structure, depauperate in species, and often low in vigor) and may not develop into biologically complex forest capable of providing diverse values (Carey 1995; Carey and Johnson 1995; Carey, Kershner, and others 1999; Carey, Lippke, and others 1999; Carey, Thysell, and others 1999; Carey and Harrington 2001). Comparisons of natural and managed forests show piecemeal management is unlikely to provide full societal value because complexity is more important than single habitat elements to both biodiversity and capacity to produce various goods and services (Carey 1995; Carey and Johnson 1995; Carey and Harrington 2001; Carey 2003a). Industrial "fiber farms" will not provide most values people seek—orderly plantations suggesting human dominance of nature, devoid of wildness and naturalness, with biological diversity intentionally suppressed. Thus, the challenge we face is how to actively and intentionally manage (AIM) 2nd-growth forests to provide the diverse values society demands.

Active Intentional Management (AIM)

AIM is a conservation approach that emphasizes a full range of active and passive management techniques to manage important ecological and hydrologic processes to conserve biodiversity and provide various goods, ecological services, and recreational and spiritual opportunities to people over the long term (Carey, Lippke, and others 1999). Active management techniques most emphasized include variable-retention harvest systems, planting and seeding multiple species of trees, precommercial thinning, variable-density commercial thinning, biological legacy retention during any harvest of trees, managing decadence to provide cavity trees and coarse woody debris, long-to-indefinite rotations, and road decommissioning, upgrading, and construction. Application is site- and community-specific, based on diagnosis, prognosis, and culturally acceptable prescriptions. AIM recognizes that "cookbook" approaches are neither ecologically nor culturally appropriate. The intentional aspect of AIM relates to its deliberate attempt to 1) produce multiple values, from wood to water to wildness (including biodiversity) from ecosystems and landscapes, 2) incorporate a wide range and depth of interdisciplinary science in a systems approach to ecosystem and landscape management (Wilbur 1995; Holling 2001), 3) involve people from various parts of the human community in collaborative learning and management, and 4) promote general (environmental, economic, and social) sustainability (Goodland 1885). Thus, AIM is distinctly different from management approaches (for example, objectives-oriented management and multiple uses, but in different places) in which a land owner or manager selects some subset of human goals and values and then manages (or neglects or reserves) forests and landscapes to achieve those goals at the expense of other social values. Such narrow-focus management often emphasizes 1 or a few disciplines (for example, silviculture or game management or reserve design) and can have both unintended consequences (for example, endangerment of salmon stocks, invasion by exotic species, epidemics of pests and diseases, and social discord) and intended consequences that may externalize costs to society at large (for example, flooding, air and water pollution, and loss of biodiversity). Landscape zoning to provide a variety of single uses and values may accentuate fragmentation and can result in cumulative effects that negatively impact soil, hydrologic processes, aquatic habitats, population viability of rare species, and diversity of native species as well as the ability to manage effectively and efficiently (Carey, Lippke, and others 1999). Restoring function to degraded landscapes entails restoring biocomplexity to 2nd-growth forests over broad areas, managing ecosystem and landscape processes and dynamics rather than static ecosystem and landscape structures, and actual physical repair of damage done to unstable slopes and to streams and repair of poorly constructed or poorly maintained transportation systems (Carey 2003b). AIM for multiple values is guided by descriptive and comparative ecological studies conducted in the Pacific Northwest and elsewhere (for example, Franklin and Dyrness 1973; Franklin and others 1981, 1987; Forsman and others 1984; Carey 1989, 1995, 2000a, 2000b; Canham and others 1990; Ingham and Molina 1991; Ruggiero and others 1991; Carey and others 1992; Carey and Johnson 1995; Carey and Peeler 1995; Carey, Thysell, and others 1996; Carey, Kershner, and others 1999; Haveri and Carey 2000; Wilson and Carey 2000; Carey and Harrington 2001), wildlife-habitat-relationships manuals (for example, Johnson and O'Neil 2001), experiments initiated in 1991 to test select assumptions and predictions of AIM (Carey 2003a provides a summary), and modeling exercises (Carey, Elliot, and others 1996; Carey, Lippke, and others 1999). The full initial literature review, including theoretical underpinnings, may be found in Carey, Elliot, and others (1996). AIM is adaptive, and draws from other past and recent studies, in particular studies like Muir and others (2002), and the works cited therein, and numerous recent experiments (see Peterson and Maguire 2005 for a summary). My purpose here is to use selected results from these studies to evaluate passive management (benign neglect after harvest), intensive management for timber, and AIM, especially the 1 key element of AIM that has been experimentally tested—inducing heterogeneity in 2nd-growth canopies to promote biological diversity.

Evaluating Alternative Management Approaches

Evaluating any kind of management requires reference conditions that represent some idealized situation (touchstones) and benchmarks that represent some starting point (for example, the status quo, current best management practices, and alternatives used by others) by which to judge success. Thus, progress from the benchmark and towards the idealized state can be measured, and the efficacy of different approaches can be compared. What would be a good touchstone for AIM? Key components for environmental sustainability include naturalness, high biodiversity that allows adaptiveness, resistance to disturbance, and resiliency in the face of disturbance. Ancient forests of the PNW, given their diverse high values and their very persistence over 250 to 1000 y that demonstrate high biodiversity and robustness in the face of change, can serve as touchstones for evaluation of long-term outcomes. Bookend benchmarks are provided by passive management and intensive management for timber. Economic sustainability can be measured by net present value of wood products (which incorporates expenses, revenues, and interest rates), sustainable revenues in the future, employment associated with the management activity and products, taxes generated, and contribution to maintaining the infrastructure for a diversified wood products industry. Given adequate data, one could model recreational value, non-timber forest products, water produced, carbon sequestration, and other values as well. More problematic is social sustainability ("maintaining a civil society"); at present, I don't think this can be adequately modeled, but it can be measured in terms of numbers of adversarial interactions, demonstrations, appeals, and lawsuits and in positive terms as well—satisfaction with collaborative management processes, donations to non-profit organizations that negotiate conservation agreements, premiums paid for certified wood products, volunteerism in aid of the land manager, participation in collaborative management efforts, and money invested in "green" timber management organizations. In addition to the use of benchmarks, touchstones, and metrics, management systems can be evaluated using 3rd-party criteria (for example the Forest Stewardship Council Certification procedure—a non-profit, non-governmental organization, the Sustainable Forestry Initiative criteria—a timber industry effort, or the Society for Ecological Restoration (SER) restoration criteria—a scientific and professional society). My other paper in this issue applies the SER criteria to AIM (Carey 2006). Here I focus on a few environmental measures and a few economic measures. First, however, I explain 2 complex measures I used throughout a variety of studies.

To develop touchstone criteria, I began with the arboreal-rodent keystone complex of the northern spotted owl (*Strix occidentalis*), northern flying squirrel (*Glaucomys sabrinus*), ectomycorrhizal fungi, and Douglas-fir (*Pseudotsuga menziesii*). This complex provides a heuristic framework for analysis and that seems to make sense to diverse publics (Carey 2000a). The spotted owl is threatened with extinction due to loss of old growth (long-lived, resilient, persistent, and naturally complex forest). The flying squirrel is the primary prey of the owl (Forsman and others 1984; Carey and others 1992). Truffles (sporocarps of ectomycorrhizal fungi) are the primary food of the squirrel (Carey 1995; Carey, Kershner, and others 1999). The squirrel disperses truffle spores and associated microorganisms throughout the forest (Li and others 1986). Mycorrhizal fungi enhance the ability of Douglas-fir (and other trees) to absorb water and nutrients from the soil and receive carbohydrates in return. The fungi move photosynthetic carbohydrates from trees to the mycorrhizosphere, a vast array of microbes, insects, nematodes, bacteria, and other soil organisms (Ingham and Molina 1991). Of course, this food chain is overly simplified. Although the flying squirrel is the primary prey of the owl in the Pacific Northwest, other species play important roles, too, especially woodrats (*Neotoma fuscipes* and *N. cinerea*) in southern Oregon and northern California (Forsman and others 1984), and their role (and the role of other species) in determining the abundance, distribution, and habitat use of the owl can be modeled (Carey and others 1992; Carey and Peeler 1995). I expanded the arboreal rodent group to account for a broader food web that includes multiple vertebrate predators. I measured the total and relative biomass (percentage due to each species) of 3 squirrels, the northern flying squirrel, Douglas' squirrel (*Tamiasciurus douglasii*), and Townsend's chipmunk (*Tamias townsendii*), in 2nd growth in Oregon and Washington and compared these abundances to the simultaneously high abundances of the 3 species in old-growth forests in Oregon and Washington, respectively (Carey and others 1992; Carey 1995, 2000b, 2003a; Carey, Kershner, and others 1999). Biomass of this species group is informative because it represents a significant portion of the energy available to medium-sized carnivores and the energy available to consumers in terms of the reproductive output of the forest ecosystem (flowers, seeds, berries, nuts, mushrooms, and truffles). The arboreal rodents are important prey for most of the medium-sized predators in the forests (including hawks, owls, weasels, felids, canids). While diets of the 3 squirrels overlap, the flying squirrel is a truffle and mushroom specialist, Douglas' squirrel is a conifer seed specialist, and Townsend's chipmunk is a fruit generalist, feeding on conifer seeds, seeds and nuts of deciduous trees, berries of shrubs, and truffles (but relegated to areas of high shrub cover). Thus, not only does the combined biomass of these 3 species reflect fruiting by plants and fungi, it also determines the carrying capacity of the forest ecosystem for a diverse assemblage of medium-sized predators. Thus, the combined biomass is a measure of ecological productivity and can be measured at the local ecosystem scale (Carey, Lippke, and others 1999). Because the niches of the squirrels overlap, simplification of forests often leads to low abundance (or even absence) of ≥1of the 3 species, but high biocomplexity can lead to simultaneously high abundance of all 3 species. However, in the next trophic level up, vertebrate predators, like the spotted owl, often respond to landscape character or regional variation in prey base (Carey and others 1992) and cannot be used to evaluate management at small scales.

For a 2nd criterion, I looked to the forest floor. Most would agree that the forest floor (litter, humus, and soil) functions as the foundation for sustainability of forest ecosystems (Carey, Thysell, and others 1996). However, it seems apparent that climate change, introduced pests and diseases, catastrophic disturbances, and epidemics of endemic diseases and pests arising from climate change and human disruption of ecological relationships can override productive soils; but the forest floor, nevertheless, remains the foundation (literally and figuratively) for the forest. Biological activity in the forest floor depends on a variety of microorganisms, fungi, and invertebrates that are important in nutrient cycling. Forest-floor invertebrates are abundant in both species and individuals with species often unknown or poorly described. Still, changes in the structure (species membership, relative abundances of species, functional groups, and the composition of functional groups) of biotic communities in response to forest management generally are more informative than changes in the abundances of single species (Carey and Johnson 1995; Carey, Thysell, and others 1996; Carey, Kershner, and others 1999; Carey, Lippke, and others 1999; Carey and Harrington 2001). Furthermore, the structure of a biotic community in old-growth forest can be used as a measure of biotic integrity against which changes can be measured. Thus, I stepped up 1 trophic level from the plants, fungi, invertebrates, and microorganisms (where functional groups seem to be the only practical way to analyze structure, given the vast number of species, many of which have yet to be described) to measure the most tractable group of organisms dependent on forest-floor diversity and function. I measured the biotic integrity (species membership and relative abundance of species compared to old forests) of the forest-floor small mammal community (*Peromyscus* spp., *Clethrionomys* spp., *Microtus* spp., *Sorex* spp., *Neurotrichus gibbsii*) that includes granivores, fungivores, herbivores, and insectivores, but which is particularly diverse in insectivores in PNW forests (Carey and Harrington 2001). In this case, biotic integrity is a better measure than biomass, because the interest is in the diversity of food webs (not their productivity) and their relative dominance in the forest floor (which also relates to shifts in relative dominance of functional groups) and because it is difficult to accurately estimate biomass of forest-floor small mammals (biomass also fluctuates markedly among years, but biotic integrity is more stable) (Carey and Johnson 1995; Carey and Harrington 2001). In other words, I measured the function of a variety of food webs in the forest floor in supporting various species of forest-floor mammals as a measure of overall forest-floor function compared to old growth. In various studies, using similar rationales, I incorporated other biotic communities (birds, ungulates, parasitic nematodes, and others) to be more comprehensive in evaluating forest function.

METHODS

Three types of studies underlie AIM: comparative or cross-sectional studies, experimental studies, and computer simulations. In the PNW, cross-sectional studies initially focused on natural forests of different ages—young (40 to 80 y), mature (80 to 200 y), and old (>200 y). In the 1980s, an interagency multi-university effort compared biotic communities in old-growth, mature, and naturally young forests in multiple physiographic provinces. Communities included vascular plants, below-ground fungi, reptiles, amphibians, birds, and mammals (summarized in Ruggiero and others 1991). These studies were expanded later to compare managed-young, naturally young, and naturally old stands with similar geographical replication, but with a focus on spotted owl habitat use, owl demography, owl prey bases, and associated food webs in natural and managed forests (for example, Carey and others 1992; Forsman and others 1993; Carey 1995; Carey and Johnson 1995; Carey, Kershner, and others 1999; Carey and Harrington 2001).

Drawing from the comparative studies, I implemented 2 experiments in accelerating development of biocomplexity in forest vegetation (high species diversity, spatial heterogeneity in overstory and understory density and composition, and diversity in the vertical distribution of foliage) by inducing heterogeneity into 2nd-growth forest canopies that was similar to that in old growth in Oregon (Fig. 1). Maps of natural mosaics had revealed 0.1 to 0.5-ha patches with a 2:1 ratio of closed to open canopy (Carey, Kershner, and others 1999). In the Puget Trough of Washington (summarized in Carey 2003a; Schowalter and others 2003) and, later, across the Olympic Peninsula (Carey and Harrington 2001), I used variable-density thinning (VDT) to create canopy mosaics in a wide variety of 2nd-growth stands (including previ-

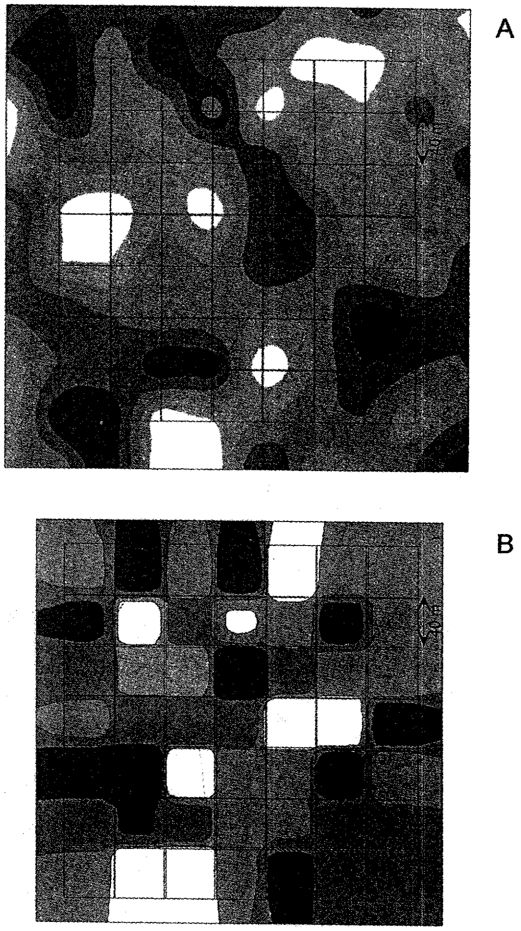

FIGURE 1. Recreating spatial heterogeneity characteristic of old forests in 2nd-growth forest canopies with variable-density thinning: (A) densities of trees >50 cm at 1.5 m above ground in a 280-y-old *Pseudotsuga menziesii* forest, shading (light to dark) represents densities from 3 to 45 trees/ha, based on 225 sampling points (from Carey, Kershner, and others 1999); (B) relative densities of *P. menziesii* >20 cm at 1.5 m following variable-density thinning of a 56-y-old 2nd-growth stand; shading (light to dark) represents relative density classes of <3.25, 3.25 to 4.75, 4.75 to 6.75, and >6.75 (from Carey, Thysell, and others 1999).

ously intensively managed with conventional thinning and removal of legacies; passively managed with legacies from old growth; and extensively managed with or without legacies, with or without thinning). I hypothesized that removing subordinate and codominant trees would make light, water, nutrients, and space available in various amounts to other vegetation though space in the thinned stand. Effects would extend beyond the altered patches of canopy because of low sun angles. Thus, fine-scale canopy heterogeneity would create an even more diverse mosaic of environmental conditions and numerous patch types in the understory (Canham and others 1990). For convenience, I will refer to stands that were subjected to VDT as *mosaics;* stands that originated after clearcutting but that still retained legacies from old growth, such as scattered large live trees, large dead trees, tall stumps of harvested large trees, and large fallen trees and associated biota as *legacy stands;* stands that had been managed intensively for timber with multiple conventional thinnings as *timber stands;* and to the common, 2nd growth stands, sampled in cross-sectional surveys, that had been created by clear cutting followed by natural regeneration, seeding, or planting and benign neglect as the diverse group, general *2nd growth.* Finally, I will refer to stands treated with VDT as legacy mosaics or timber mosaics.

In 1994, I led a team modeling alternative approaches to landscape management, including AIM to conserve biodiversity (Carey, Lippke, and others 1999; Carey 2003b). Three final landscape management scenarios were chosen for full evaluation: protection with no manipulation (passive management), management to maximize net present value of wood production, and AIM for a multiplicity of values. Alternatives were evaluated on ability to maintain spotted owls (a threatened species), capacity to support vertebrate diversity (based on 130 species), relative forest-floor function (biotic integrity of the small mammal community), 2 measures of ecological productivity (biomass of arboreal rodents and numbers of deer and elk), timber productivity, and timber revenues.

RESULTS

Comparative Studies

In the PNW, natural forests and contemporary managed forests differ in structure, composition, and function (Carey 1995; Carey and Johnson 1995; Carey, Kershner, and others 1999; Haveri and Carey 2000; Thysell and Carey 2000; Wilson and Carey 2000; Carey and Harrington 2001; Carey and others 2002;

Franklin and others 2002). In natural forests, many elements of the ecosystem are patchily distributed. These elements include live trees from the preceding stand, large fallen trees, trees with cavities used for denning and nesting, berry-bearing shrubs, deciduous trees, shade-tolerant trees in the midstory, forbs, mosses, and fruiting bodies (truffles) of ectomycorrhizal fungi, among others. Groups of these elements may be correlated in their occurrences due to topographic effects or canopy gap formation and, thus, form distinct patches. Diverse patches, arrayed in fine scale, contribute to emergent properties, such as simultaneously high abundances of potentially competing species that do not occur together in high abundances in large, homogeneous patches. The scale of variation in arrangement that contributes to this synergy is about 0.1 to 0.5 ha, or 80 to 100 m (Canham and others 1990; Carey, Kershner, and others 1999). Biotic legacies from the preceding forest, propagules from adjacent stands, forest structuring processes, and development of spatial heterogeneity interact to produce both overall compositional diversity and patch diversity (Carey, Kershner, and others 1999; Franklin and others 2000). In contrast, timber management, particularly even-age management, purposefully reduces spatial heterogeneity and compositional diversity (Carey 2003a; Carey and Harrington 2001). Consequently, the response of species to changes in abundances of particular elements of their habitat varies from place to place in managed forests, in relation to the relative abundances of other ecosystem elements. The diversity and structure of vertebrate communities, however, varies consistently in response to complexity of vegetation structure and absence of various compositional elements because spatial heterogeneity and compositional diversity in plant and fungal communities is prerequisite to niche diversification, animal community diversity, and the ability of ecosystems to resist or recover from disturbance (Hutchinson 1958, 1978; Carey, Kershner, and others 1999; Tilman 1999). Forest management can promote this biocomplexity (Carey, Kershner, and others 1999; Carey, Lippke, and others 1999; Lindenmayer and Franklin 2002). Retention of legacies of individual live trees, dead trees, coarse woody debris, or even patches of forest can be used with even-age or uneven-age management systems (Franklin and others 2000). Variable-retention harvest systems transcend traditional silvicultural conventions (Lindenmayer and Franklin 2002). Thinning influences all structuring processes, including decadence and development of spatial heterogeneity. Thinning with underplanting restores diversity of tree species and accelerates canopy stratification and understory development (Thysell and Carey 2001). Retaining decadent trees, wounding trees, and inoculating trees with top-rot fungi promote decadence essential to ecosystem development (Carey, Kershner, and others 1999).

Experimental Results

Fungi.—Past management influenced soil food webs, but all retained fungi-dominated soils (Carey, Lippke, and others 1996; Carey and others 2002). Fungal to bacterial biomass ratios (total fungal to total bacterial biomass and active fungal to active bacterial biomass) were higher in legacy than in timber stands for total biomass and for active biomass, however. Fungal mats covered ⅔ of the forest floor in legacy stands but only ¼ in timber stands. Compared to controls, VDT had no effect on total biomass ratios, but increased active biomass ratios in both timber mosaics and legacy mosaics. Total fungal biomass remained unchanged in timber mosaics but decreased in legacy mosaics. Truffle biomass averaged 0.5 kg/ha (ranging 0 to 1.8 kg/ha seasonally) in untreated timber and legacy stands. Of 28 species found in timber and legacy stands, 19 were in timber with 7 only in timber stands and 21 were in legacy stands with 9 only in legacy stands. *Rhizopogon* was the dominant genus, with a relative frequency of 40 to 47%. *Gautieria* and *Leucogaster* were more frequent in legacy than in timber stands and *Melanogaster* and *Hysterangium* were more frequent in timber stands. Truffle production was reduced overall in mosaics (from an overall frequency of 18% in control plots to 13% in VDT plots) in the short term, with heavily thinned patches most reduced (to 10%). Truffle diversity increased to 48 species in mosaics (vs. the 28 species in controls) and productivity quickly recovered. *Gautieria* and *Hysterangium* decreased in abundance in mosaics, but *Melanogaster* increased in species diversity and biomass. A total of 64 mushroom species were found before treatment, 37 (19 mycorrhizal) in legacy stands and 44 (15 mycorrhizal) in timber stands. Richness of ectomycorrhizal mushrooms was highest in legacy stands. After VDT, 108 mushroom species were found in legacy mosaics (vs. 89 species in legacy controls) and 78 species were found in timber mosaics (vs. 65 in timber controls).

Vascular Plants.—Legacy stands had 27 to 40 species of understory plants compared to 49 to 87 species per timber stand. Of 91 total species in all timber stands, 51 were not found in legacy stands and 18 were nonnative (1 tall shrub, 2 low shrubs, 13 herbs, and 2 grasses). Of 47 total species in all legacy stands, 4 were not found in timber stands, including the old-growth associate Pacific yew (*Taxus brevifolia*), and 1 was nonnative (Thysell and Carey 2000). Community structure differed with management history, with timber stands dominated by aggressive clonal native shrubs and ferns. Timber stands had greater cover than legacy stands for total understory (88% vs. 34%), tall shrubs (12% vs. 5%), salal (25% vs. 13%), swordfern (16% vs. 3%), and brackenfern (9% vs. 2%). Compared to controls, mosaics initially had reduced understory cover and increased importance of 20 native and 11 exotic species (Thysell and Carey 2001). Two native species decreased in importance. Three years later, understory recovered, species richness increased by 150%, only 4 exotic species persisted in importance, and 8 natives increased and 7 natives decreased in importance. Underplanting in mosaics established root-rot-resistant trees in root-rot pockets, increasing the resilience of the forest, and in other heavily thinned areas, increasing resistance to spread of root rot. After 10 y, some exotic species persisted at low levels and spatial patterning was beginning to emerge in the understory. Sparse natural regeneration of shade-tolerant conifers, markedly increased abundance of understory hardwoods, and good survival of underplanted trees of high to intermediate shade tolerance portends a rapid increase in understory diversification.

Small Mammals.—Timber stands had 1.5 times the numbers and 1.7 times the biomass of small mammals in legacy stands. Keen's mouse (*Peromyscus keeni*), a dominant species in natural forests, was rare in both legacy and timber stands (Wilson and Carey 2000). The creeping vole (*Microtus oregoni*) was inordinately abundant in timber stands (3rd ranked) compared to legacy stands (7th ranked) and natural stands. The montane shrew (*Sorex monticolus*) was also inordinately abundant in thinned stands (2nd ranked). Neither management history produced communities typical of natural forests. After VDT, deer mice (*Peromyscus maniculatus*), creeping voles, and vagrant shrews (*Sorex vagrans*) increased in abundance in mosaics (Carey and Wilson 2001). No species decreased in abundance. Northern flying squirrels were twice as abundant in legacy as in timber stands (1.0/ha vs. 0.5/ha) (Carey 2000). Townsend's chipmunks were opposite (0.2/ha vs. 0.8/ha). Douglas' squirrels were low in abundance in both timber and legacy stands (0.1/ha). Flying squirrels decreased in abundance in legacy mosaics immediately following VDT but recovered within 5 y. Chipmunks increased sharply in legacy mosaics following VDT and remained high (Carey 2001). Douglas' squirrels did not respond to VDT in the short term. It remains to be seen whether flying squirrels and Douglas' squirrels will increase over time in mosaics as tree diversity increases and as trees increase photosynthetic activity and allocate additional carbon to seeds and ectomycorrhizal associates. California hazel (*Corylus cornuta*) and bigleaf maple (*Acer macrophyllum*) are present, growing, and producing nutritious nuts and seeds for the squirrels in response to the more open canopy (increased light).

Wintering Birds.—In cross-sectional studies of birds in natural forests, resident (overwintering birds) showed greater sensitivity to decreased complexity than spring migratory birds (Manuwal and Huff 1987), thus in the experimental studies, we examined wintering birds (Haveri and Carey 2000). Species richness averaged 16 in timber stands, but only 12 in legacy stands. Richness remained unchanged in timber mosaics, ranging from 14 to 22 species 3 to 5 y after VDT. Richness varied annually but was consistently higher in legacy mosaics than in legacy controls 3 to 5 y post-VDT (annual richness was 12 to 16 species in mosaics vs. 10 to 16 species in controls). The proportion of stand area used increased in mosaics for 2 of 8 abundant species (*Troglodytes troglodytes* and *Melospiza melodia*). No species used legacy more than timber or mosaic stands. Cav-

TABLE 1. Measures of landscape function in a western Washington landscape in the last 100 y of a 300-y simulation under management to maximize net present value of timber and active intentional management for multiple values.

Ecological measure	Timber management	Biodiversity management
Vertebrate diversity (% of maximum possible)	64	100
Forest floor function[a] (% of maximum possible)	12	100
Ecological productivity[b] (% of maximum possible)	19	94
Overall function (mean of the above 3)	32	98

Source: Adapted from Carey, Lippke, and others (1999)

[a] Composition and structure (relative abundances) of the forest-floor small mammal community measured against that in old growth.

[b] Biomass of northern flying squirrels, Townsend's chipmunks, and Douglas' squirrels measured against that in old growth.

ity-excavating birds (Picidae) were present, but low in abundance, in all stands.

Modeling Results

Simply protecting 2nd growth caused the landscape to go through waves of forest development (Carey, Elliot, and others 1996; Carey, Lippke, and others 1999). Initially a substantial ecological crunch occurred because of degraded watersheds and oversimplified stands; a long time (200 y) was required for these stands to achieve an old-growth-like condition. Timber management with minimum constraints produced a landscape inhospitable to >20 vertebrate species and allowed no recovery of degraded streams; its sustainability was uncertain, but net present value was maximal. Timber management with riparian reserves drawn from federal guidelines, produced relatively narrow, well-separated strips of late-seral forest in the long term, unlikely to function fully as late-seral forest because of their continued adjacency to clearcut and young forests; clearcutting was intensified in the available uplands due to removal of streamside and adjacent small patches from forest management. Biodiversity management, as it was designed to do, produced significant ecological benefits (Table 1), including supporting a pair of spotted owls and numbers of deer and elk comparable to the timber management regime. AIM costs were surprisingly low—only a 15% loss in net present value compared to maximizing net present value of timber extraction. Assuming (as occurred) increased riparian protection would be mandatory and eliminating costs of improved riparian and mass-wasting management from comparisons, AIM resulted in only a 6% decrease in net present value. Other economic values increased: decadal revenues increased by 150%, forest-based employment quadrupled, and the wood products manufacturing sector diversified and relied more heavily on high quality wood products and value-added manufacturing (Lippke and others 1996). Initially, I included a constraint of 30% of the landscape in late-seral forest to support 1 pair of spotted owls; the final shifting steady state mosaic maintained >50% of the landscape in late seral stages and <15% of the landscape was in clearcuts in any decade, resulting in a landscape fully permeable to dispersing late-seral species.

DISCUSSION

Similarity between fungal communities in timber and legacy stands suggests high resiliency in soil food webs in the face of active management (Carey and others 2002; Carey 2003a; Schowalter and others 2003). Timber management, however, reduced fungal dominance and macroscopic fungal mats. Mechanical disturbance appears to destroy fungal mats and promote *Melanogaster* over *Hysterangium* and *Gautieria*. Impacts on truffle production, however, were brief. The long-term impacts of forest management on truffle production remain unclear, with inconsistent results from across the region (Carey and others 2002; Smith and others 2002). Induced heterogeneity increased sporocarp diversity to a richness that rivals that in old growth (Carey and others 2002). Retaining unthinned patches in mosaics might help conserve fungal mats and allow their recolonization because increased photosynthetic activity by trees increases the flow of carbohydrates to soil food webs and maintains high fungal diversity.

Conventional thinning produced timber stands with species-rich understory vegetation dominated by clonal natives with numerous exotics present. Achlorophyllous mycotrophs (parasitic plants without chlorophyll) were reduced in abundance by dense understory; retaining unthinned patches in mosaics would help conserve these species. Understories in the timber stands, however, lacked both shade-tolerant trees and the spatial heterogeneity associated with diverse vertebrate communities (Carey, Kershner, and others 1999). Legacy forests had depauperate understories and low abundances of small mammals and wintering birds. Thus, neither historical management regime had placed stands on a trajectory toward developing the complexity and diversity of old-growth forests. Inducing mosaics increased diversity and abundance of native species, but only slightly increased exotics. Underplanting is leading to increased spatial heterogeneity. It now appears likely the course of both timber stands and legacy stands has been altered by inducing heterogeneity and that development of biocomplexity, although far from ensured, is more likely than before treatment.

Timber and legacy management produced imbalanced mammal communities, with some species that are common in natural forests being low in abundance in the managed stands. Inducing heterogeneity had immediate positive effects on forest-floor mammals, but shade-tolerant midstories and midstory deciduous trees, such as bigleaf maple, will help restore the structure of the community. Chipmunks increased markedly in legacy mosaics with only brief declines in flying squirrels. Flying squirrels remained rare (some of the lowest densities ever recorded in PNW) in the timber stands, perhaps due to open canopies that impede arboreal travel and dense understories that promote excessive chipmunk abundance, make foraging for truffles more difficult, and increase exposure to predation by large gaps between the understory and canopy. Heterogeneity had positive effects on winter birds; cavity-excavating birds, however, remained low in abundance. Promoting deciduous trees early in stand development provides both short-lived trees (*Alnus rubra*) for cavity excavation and long-lived trees (bigleaf maple and Pacific madrone [*Arbutus menziesii*]) for mammal dens. Legacy retention and decadence management is essential to maintaining cavity-excavating birds and forest-floor organic matter. It seems that intentional disturbance can produce spatial complexity at the fine scale that is important in restoring and maintaining biodiversity in 2nd-growth temperate, boreal, and tropical forests (Canham and others 1990; Carey, Kershner, and others 1999; Carey, Lippke, and others 1999; Franklin and others 2000, 2002; Lindenmayer and Franklin 2002).

Natural history, comparative, experimental, and modeling studies have demonstrated: the value of diverse ecosystem elements from headwater seeps to fallen trees to deciduous components of conifer ecosystems; the importance of spatial heterogeneity in both the vertical and horizontal dimensions and within individual structures; temporal change (seasonal, interannual, decadal, and submillenial dynamics) and adaptation to changing environmental conditions; and small, intermediate, and large-scale disturbances as underpinnings of biodiversity and biocomplexity. Managerially induced homogeneity favors some species over others resulting in a loss of biotic integrity, most benefiting globally abundant species and exotic species. No active management after clearcutting also results in loss of biological diversity and biotic integrity. Computer simulations suggest that AIMing for multiple values can produce wood; water; clean air; recreational opportunities; revenues to the land manager, owner, or trust; biological diversity; viable populations of species associated with old forests; and healthy aquatic systems. Simulations of maximizing net present value of wood and protecting forests without manipulation forecast reduced values, including reduced sustainable revenues, higher risks of loss of values, new costs, and lack of opportunity for the ecosystems to adapt to change. AIM, however, requires a suite of techniques, beginning with public involvement in setting goals and strategies to accomplish goals. Next, geotechnical analysis of watersheds can be used to identify areas of unstable slopes and potentially erodable colluvium that, along with headwater seeps and streams, and larger, fish bearing streams, can be buffered appropriately and provide a template for legacy retention. Watershed analysis is followed by design, construction, rehabilitation, and maintenance of efficient and low-impact transportation systems. Intentional ecosystem management then incorporates modern silvicultural methods arrayed into management pathways that provide for directional development of ecosystems in shifting steady-state mosaic landscapes. These methods might include variable-retention harvest systems that emphasize legacy retention as much as wood removal, multispecies planting, precommercial thinning to promote growth and biodiversity, multiple variable-density commercial thinnings to harvest wood while protecting legacies and inducing spatial heterogeneity to stimulate development of biocomplexity, multispecies management that includes deciduous trees and shrubs in conifers forests, and long or alternating long and short rotations. AIM has potential to contribute to economic, social, and environmental sustainability.

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