Intentional Systems Management: Managing Forests for Biodiversity

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ABSTRACT. Conservation of biodiversity provides for economic, social, and environmental sustainability. Intentional management is designed to manage conflicts among groups with conflicting interests. Our goal was to ascertain if intentional management and principles of conservation of biodiversity could be combined into upland and riparian forest management strategies that would be applicable to various land ownerships and, consequently, help resolve land allocation problems associated with timber supply and threatened wildlife.

We used computer simulations to model three divergent management strategies for Pacific Northwest western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) forests: preservation with no manipulation (NMP), maximizing net present value (npv) through timber and fiber produc-

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tion (TFP), and conservation of biodiversity (CBD) with intentional ecosystem management. We evaluated costs and benefits of alternatives. Economic measures included npv of timber, sustainable timber revenues, total and sustainable volume of wood products, and quality premiums for wood products. Ecological measures included capacity to support vertebrate diversity, forest floor function based on the integrity of the forest-floor mammal community, ecosystem productivity based on the biomass of the arboreal rodent community, and production of wild ungulates. Index values were assigned to seral stages and aggregated across landscapes to evaluate conditions over 300 years.

No manipulation resulted in long periods of competitive exclusion that could cause species declines or extirpations. When combined with TFP, wide riparian buffers removed 35% of the landscape from active management, >200 years were required to obtain 30% late seral-forest, late-seral forest were badly fragmented by intervening intensively managed forest, and npv = $48.5 million. Small buffers and TFP resulted in no late-seral forest, ≥25 species at risk (not counting fish), and maximum npv, $70.3 million. CBD provided (1) 30% late-seral forest in 80 years and 52% late-seral forest in the long term, (2) enhanced riparian systems, (3) recovery of sensitive species, (4) npv = $58 million, 82% of maximum npv, and (4) maximum sustained decadal income. Transition costs from present to regulated ("steady") state were large. Net present values of cost for each 10% increase in late-seral forest were as low as $247/landscape ha; costs per designated ha ranged from $1,235 (age 0) to $3,700-4,940 (age 30). Intentional management based on CBD is a net benefit solution for multiple-use and trust lands. *[Article copies available for a fee from The Haworth Document Delivery Service: 1-800-342-9678. E-mail address: getinfo@haworthpressinc.com <Website: http://www.haworthpressinc.com>]*

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INTRODUCTION

Human activities are pervasive influences on most landscapes. Worldwide, we are in a period of ever-worsening ecological crisis caused by economic, social, and political decisions that can be averted only by changes in human institutions and values (Brussard 1991). If we are to keep options alive for ourselves and for future generations, we must manage to conserve biodiversity (Reid and Miller 1989). 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 generation's needs and aspirations (Reid and Miller 1989, IUCN 1980).

Biodiversity includes all the building blocks of the living world (genes, individual organisms, species populations, biotic communities, and ecosystems), the ecological and evolutionary processes that incorporate and shape these blocks, and the resulting ecological and economic goods and services (Reid and Miller 1989, di Castri and Younes 1990). Conservation of biodiversity is a foundation for sustainable forestry (wood cannot be grown unless living trees can avail themselves of the nutrients and water of the ecosystem) as well as for viable populations of wildlife; thus, opportunity exists for reconciling artificial conflicts between conserving wildlife and maintaining wood production. But, people differ in their world views and there is serious disagreement about how to manage for multiple values, the costs of such management, and even if such management is possible.

Our goal was to develop the paradigm of conservation of biodiversity into a strategy for forest ecosystem management that could be applied across land ownerships (public and private) and that would provide for joint production of timber and wildlife in the context of environmental, economic, and social sustainability (general sustainability, Goodland 1995) in western hemlock (*Tsuga heterophylla* [Raf.] Sarg.)-Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests in the Pacific Northwest United States. This strategy would be sharp contrast to existing *de facto* allocations of land in the Pacific Northwest either to intensive management for timber or to reserves with little active management. In particular, we wanted to develop management pathways that would not only deliberately address the needs of all indigenous wildlife, including wildlife associated with old-growth forests (e.g., Carey 1989), but also diverse societal wants and needs from forests. Our approach is generally applicable to Western Hemlock Zone forests of western Washington and western Oregon (Franklin and Dyrness 1973; generally, coniferous forests < 1200 m elevation), where there has been substantial controversy over maintenance of viable populations of wildlife associated with old-growth forests and the impact of species conservation efforts on timber production. The theory and concepts behind the approach are even more widely applicable. Our approach to conservation of biodiversity is syncretic and hierarchical; it begins with ecosystem management, is implemented through landscape management, and produces regional, long-term benefits. We provide principles, procedures, and recommendations for conservation of biodiversity that apply to (1) second-growth forests now managed primarily for wood products (state and private timberlands), (2) second-growth forests managed for restoration of ecological function as habitat for wildlife associated with late seral stages of forest development (late-successional reserves and adaptive management areas on federal lands) and ecological services (e.g., water, carbon sequestration), and (3) streamside, second-growth forests managed as late-successional biodiversity reserves to enhance riparian and landscape function. Because many benefits of intentional management accrue to society and not to the landowner, but most costs accrue primarily to the landowner, we paid special attention to calculating costs and benefits of alternative approaches. Costs and benefits can provide guidance in developing incentive programs to encourage private landowners to manage for multiple benefits.

STUDY AREA

We used the Clallam River Planning Area of the Olympic Experimental State Forest, Washington Department of Natural Resources, for our simulations. Area managers had assembled complete and complex data on stand conditions, locations, and sizes; distances from timber markets; suitability for harvest by alternative harvest methods; existing and potential road networks; stream reaches; and mass- wasting areas into a spatially based scheduling and harvest simulator (SNAP-II).

Clallam River is on the western Olympic Peninsula, which is characterized by high rainfall (>250 cm/yr), long growing seasons, rapid changes in elevation from the Pacific Coast to the Olympic Mountains, relatively short riparian systems beginning in mountains, descending through U-shaped glacial valleys, and emptying into the Pacific Ocean. Plant communities belong to various series in the Sitka spruce (*Picea sitchensis* [Bong.] Carr.)-western hemlock associations, western hemlock-western redcedar (*Thuja plicata* Donn ex. D. Don) associations, and western hemlock-Douglas-fir associations (Franklin and Dyrness 1973). Forest-floor small mammal communities are productive and diverse (Carey and Johnson 1995). Arboreal rodent communities support fewer species and far fewer total numbers of individuals (and biomass) than forests to the south (Carey 1995). Thus, the area supports lower densities of spotted owls (*Strix occidentalis* Xántus de Vesey) than forests to the south (Carey et al. 1992). Most of the forests burned 280-350 years ago, but windstorms have been a more frequent cause of forest stand disturbance. The last catastrophic windstorm struck the western Peninsula in 1921. Logging began in the late 19th century and was a major force shaping the forested landscapes by the 1920s (Henderson et al. 1989). When planners described the area in 1993, it was mostly second-growth, closed-canopy, even-aged stands; 94% were < 80 years old. There were no late-seral forests. Most of the riparian zones were dominated by red alder (*Alnus rubra* Bong.), with only scattered conifers.

METHODS

We began by proposing a unifying theme for forest management–reconciliation of the varied societal demands on our forests: maintenance of the property rights and profits of landowners through commodity production, preservation of species, protection of environmental health, and sustenance of forest-based human communities. This theme is general sustainability (Goodland 1995). Next, we developed a theoretical framework for management of biotic communities based on stages of forest development and the wildlife and vegetation associated with them. Then, we constructed three approaches to managing riparian areas and three broad strategies for landscape management: (1) no manipulation with protection (NMP), (2) maximization of net present value (npv) through timber and fiber production (TFP), and (3) conservation of biodiversity (CBD). We simulated TFP under two common guidelines for riparian management and CBD with a newly developed approach to riparian management. We designed and simulated numerous management pathways (similar to silvicultural prescriptions) using combinations of strategies, but we report only the three prototypes here. We identified measures, for values often mentioned in public debate, by which we could evaluate alternative scenarios (1) npv of wood products, (2) sustainability and even flow of wood products, (3) the numbers of deer and elk as an ecological recreational-commercial-indicator, (4) the integrity of the forest-floor small mammal community as an indicator of biotic integrity and forest-floor function, (5) the biomass of the arboreal rodent community as an indicator of ecosystem function and productivity and carrying capacity for predators such as mustelids and spotted owls, and (6) an index to capacity to support diverse vertebrate species based on published habitat relationships of amphibians, reptiles, birds, and mammals.

We assembled data specific to the study area, using results from on-the-ground research on the western Olympic Peninsula. We simulated landscape dynamics with the Scheduling and Network Analysis Program (SNAP-II, Sessions et al. 1997) and growth and yield of timber with the Washington Department of Natural Resources Intensive Management Program Simulator (DNRIMPS), a model specific to western Washington (Table 1). We applied our measures of biodiversity to the results of 300 years of simulated management under different strategies and mixtures of strategies. We estimated the benefits accruing to the landowner and society and the costs to the landowner in foregone timber revenues. In the discussion, we identify intangible benefits to the landowner and to society and some incentives that government might use to reduce the costs of conserving biodiversity. Lippke et al. (1996) provide a more extensive discussion of economics.

Stages of Forest Development: A Framework for Management

Development of managed forest stands can be divided into as few as four broad stages: stand initiation, stem-exclusion, understory reinitiation, and old

TABLE 1. Diameter-breast-height (dbh) and cumulative volumes of timber (10^3 m^3/ha) produced under various strategies: no manipulation, protection (NMP); timber-fiber production (TFP) with precommercial thinning at 15 years (PCT15) and harvest at 50 years; conservation of biodiversity (CBD) with planted Douglas-fir, PCT15, and variable-density thinning (VDT) at 30, 50, and 70 years.

Pathway	Year 40	Year 60	Year 80	Year 100	Year 120
Dbh (cm)					
NMP	31	41	45	47	48
TFP	33	–[b]	33	36	–[b]
CBD	39	54	64	73	76
Volume[a]					
NMP	2.2	4.2	6.5	8.4	8.9
TFP	2.5	–[b]	4.7	7.7	–[b]
CBD	2.4	4.7	6.3	7.6	8.5

[a] Total volumes (harvested and standing) converted from thousand board feet/acre (Scribner volumes) to 10^3 m^3/ha with a factor of 9.555; ingrowth is not included.

[b] Mean dbh and volumes not calculated for stands < 30 years old.

growth (Oliver and Larson 1996). Four stages, however, are insufficient for modeling various trajectories biotic communities can follow under different strategies and intensities of management. Here we use a new, expanded classification of forest ecosystem development (Carey and Curtis 1996, Table 2). The classification has eight stages because of the unique longevity, structure (especially the large amounts of coarse woody debris), and organization of Pacific Northwest old growth and the variety of organisms it supports (Franklin et al. 1981, Ruggiero et al. 1991). A detailed rationale for the eight stages was provided by Carey et al. (1996a, available on request).

Three Alternative Strategies for Landscape Management

Protection-No Manipulation Strategy–The NMP is commonly suggested for reserves and provides a base against which other strategies can be compared. Its purpose is to allow biotic communities to develop unhindered and unaided by direct, conscious, human intervention and to minimize disturbance and risks associated with active management activities such as road building and timber harvests. However, an often unstated consequence of NMP is a slow rate of forest development. There is no assurance that second-growth forests will develop similarly to ecosystems developing after natural, catastrophic disturbances because second-growth forests often are overstocked with trees and lacking in biological legacies. The NMP pathway we developed was based on quick regeneration by western hemlock following clearcutting and burning; early development was the same as under timber management without precommercial thinning.

TABLE 2. Seven prototypical stages of forest ecosystem development in managed forests the Western Hemlock Zone of Washington and Oregon.

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 forest ecosystem.
Competitive exclusion	CES	Occurs only when trees fully occupy the site and compete with one another for light, water, nutrients, and space such that most other vegetation is precluded and many trees become suppressed and die.
Understory reinitiation	URS	Light or spatially heterogeneous regeneration or achievement of dominance by some trees and death or removal of other trees (with resultant reduced competition) allows an understory plants to establish.
Developed Understory	DUS	Understory of forbs, ferns, shrubs, and trees developed after death or revmoval of some dominant trees; time has been insufficient for diversification of the plant community.
Botanically diverse	BDS	Organization and structure of the living plant community becomes complex with time but lack of coarse woody debris and other biological legacies preclude a full, complex, biotic community.
Niche diversification	NDS	The biotic community becomes complex as coarse woody debris, cavity trees, litter, soil organic matter, and botanical diversity increase; diverse trophic pathways develop; wildlife foraging needs are met.
Fully functional (managed)	FFS	Additional development provides habitat elements of large size and interactions that provide for the life requirements of diverse vertebrates, invertebrates, fungi, and plants.

The Timber and Fiber Production Strategy–TFP is market-driven; decisions usually are based on maximizing npv of wood products given minimal regulatory constraints such as the Washington Forest Practices Board (WFPB) direction on riparian areas and unstable slopes. We simulated numerous examples of timber management prescriptions provided us by land managers and chose the one that maximized npv: clearcutting, precommercial thinning at 15 years, and harvest at 40 or 50 years with WFPB minimum riparian buffers (TFP-Narrow). We also simulated TFP with wide riparian buffers (TFP-Wide) similar to those designed by the federal Forest Ecosystem Management Assessment Team (FEMAT 1993). Based on current practice on the western Olympic Peninsula and inquiries of large landowners, planting of Douglas-fir, snag management, and conservation of coarse woody debris were not part of the management prescription.

The Conservation of Biodiversity Strategy–CBD builds upon experience gained from application of alternative silvicultural practices and recent information from research (Carey et al. 1996a, b; Carey and Curtis 1996; Curtis and Carey 1996). It focuses on integration of the diverse values people derive from forests. Our biodiversity prescriptions arose, in part, out of concerns about the northern spotted owl and other wildlife associated with old forests in Oregon and Washington. Analyses of factors influencing the spotted owl, other wildlife dependent on old-growth forests, and communities of resident forest birds, arboreal rodents, and forest-floor small mammals revealed dependence on multiple and diverse habitat elements, with either overall abundance or species richness of communities increasing with stage of forest development (Carey 1989, 1995, 1996; Thomas et al. 1990; Carey et al. 1991, 1992, 1996a, b; Ruggiero et al. 1991; Carey and Johnson 1995). Old forests have a more complex structure and larger three-dimensional physical space than young forests (Carey 1998, Carey et al. 1999), i.e., increased habitat space and preinteractive niche diversification (Hutchinson 1978). We used this information, and data on growth, yield, and market value of trees, to formulate our specific objectives, or desired future condition, for ecosystem management for CBD and to identify the management practices that would create the desired future condition. A full exposition of this rationale was provided by Carey et al. (1996a).

We developed several management prescriptions and chose the one that provided the best mix of benefits: clearcutting with retention of biological legacies, planting widely-spaced Douglas-fir, natural regeneration of western hemlock and other conifers, precommercial thinning favoring multiple species at 15 years, and variable-density thinnings (Carey 1995, Carey and Curtis 1996) at 30 and 50 years with final harvest at 70 years alternating with variable-density thinnings and 30, 50, and 70 years and final harvest at 130 years with a goal was to achieve and maintain ≥30% of the landscape in late-seral forest (20% niche diversification, 10% fully functional). Variable-density thinnings included coarse woody debris augmentation and cavity-tree management costs and benefits. Every hectare of the forest had to be managed except no-entry 9-m buffers on Class 5 streams; the remainder of the riparian zone was managed with biodiversity thinnings only.

Ecological Evaluation of Simulation Scenarios

Karr (1991) concluded that a biological system can be considered healthy when its potential is realized, its condition is stable, its capacity for self-repair when perturbed is preserved, and minimal external support is needed. He developed an index to the health of streams based on the biotic integrity of aquatic arthropod communities and suggested ecological health and biotic integrity are the same. Biotic integrity was defined as the ability of an environment to support and maintain a biota comparable to the natural habitats of the region (Karr 1991). Karr (1991) also suggested that a broadly based, ecologically sound, multiparameter approach is necessary to evaluate ecological condition.

We were concerned also with (1) the ability of landscapes under different management systems to support viable populations of indigenous wildlife; (2) ensuring long-term productivity of the forest ecosystems through maintenance of healthy forest-floor communities of microbes, arthropods, and fungi; (3) the capacity of the landscape to support wide-ranging predators; and (4) the capacity of the landscape to support traditional subsistence and sport hunting of wild ungulates. Following Karr's (1991) approach, we developed a suite of four measures with which we could evaluate seral-stage contributions to biodiversity and different landscape management strategies.

A Measure of the Capacity to Support Vertebrate Diversity–The first measure we developed was an index to the diversity of wildlife that would be expected to be maintained by a stage of ecosystem development, if it existed in large quantities. We included only species that are known to occur regularly on the western Olympic Peninsula and whose primary habitat is western hemlock-Douglas-fir forest or the streams and rivers in such forests. We based our scores on data provided in Brown (1985), modified to fit our seral stages and updated by information in Nussbaum et al. (1983), Ehrlich et al. (1988), Carey (1995), Ruggiero et al. (1991), Leonard et al. (1993) and Carey and Johnson (1995) and Table 3.

Brown (1985) identified stand conditions (seral stages) as primary or secondary for each of three purposes by species: breeding, feeding, resting. We evaluated a stage as 1 for a species, if it was secondary for one or two purposes; 3, if it was secondary for all three purposes; 6, if it was primary for one or two purposes; and 9, if it was primary for all three purposes. Not all species occurred in all stages (Table 4). We summed the scores by stage to obtain relative scores of capacity of each stage to support diverse higher life forms and calculated landscape capacity values by first multiplying scores by area for each stage, summing the score-areas, and dividing by the total area multiplied by maximum score (for managerial fully functional forest) to obtain a percentage of potential capacity to support diversity of higher endemic life forms. These scores were used as part of an index to ecosystem function and to answer the question: Are all the essential elements of habitat in place and interacting in such a way as to produce a diversity of wildlife?

An Index of Biotic Integrity–The diversity of the forest-floor mammal community on the Olympic Peninsula is a result of accumulation of organic

TABLE 3. Hypothetical occurrences of selected habitat elements in different stages of ecosystem development in Western Hemlock Zone forests managed under timber production or biodiversity pathways, following clearcutting on the western Olympic Peninsula, Washington.

	Pathway/Stage[a]								
	Timber production					Biodiversity			
Element	EIS	CES	URS	DUS	BDS	URS	DUS	NDS	FFS
Cavity-trees > 50-cm dbh, >15/ha	no	no	no	no	no	no	yes	yes	yes
Coarse woody debris, ca. 15% cover	no	no	no	no	no	no	no	yes	yes
Foliage height diversity, > 2 BPI[b]	no	no	no	yes	yes	yes	yes	yes	yes
Trees >100-cm dbh, >10/ha	no	no	no	no	no	no	no	yes	yes
Deep forest-floor, litter and humus	no	no	no	yes	yes	yes	yes	yes	yes
Conifer species >2 and Douglas-fir	no	no	no	no	no	yes	yes	yes	yes

[a] Ecosystem initiation (EIS), competitive exclusion (CES), understory reinitiation, (URS), developed understory (DUS), botanically diverse (BDS), niche diversification (NDS), and fully-functional (FFS).
[b] Berger-Parker Index; see Carey et al. (1992) or text.

TABLE 4. Vertebrate species unique to the Ecosystem Initiation Stage (EIS) of forest development, the timber and fiber production pathway (TFP), the biodiversity pathway (CBD), and rivers, streams and streamsides (RSS) on the western Olympic Peninsula, Washington.

Species group	EIS	TFP	CBD	RSS
Amphibians[a]	0	0	2	3
Reptiles[b]	1	0	0	0
Birds[c]	0	0	12	1
Mammals[d]	1	0	0	7
Total	2	0	14	11

[a] CBD: *Ensatina eschscholtzii* Gray; RSS: *Dicamptodon copei* Nussbaum, *Rhyacotriton olympicus* Gaige, and *Plethodon vandykei* Van Denburgh in seeps and streams under CBD but not TFP.
[b] EIS: *Gerrhonotus coeruleus* Cope.
[c] CBD: *Brachyramphus marmoratus* Gmelin, *Strix occidentalis* Xanthus de Vesey, platform-nesting birds, and cavity-using; RSS: *Histrionicus histrionicus* Linnaeus.
[d] EIS: *Lynx rufus* Schreber (Brown 1985); RSS: *Sorex bendirii* Merriam, *Sorex palustris* Richardson, *Procyon lotor* Linnaeus, *Lutra canadensis* Schreber, *Mustela vison* Schreber, *Castor canadensis* Kuhl.

matter on the forest floor and prominence of herbaceous plants in the understory (Carey and Johnson 1995). The small mammals have diverse food habits and foraging strategies, ranging from consumption of fruiting bodies of ectomycorrhizal fungi that assist trees in nutrient and water uptake to eating insects that break down dead wood and release nutrients to the ecosystem. We evaluated the ability of each seral stage to support a complete community: Columbian deer mouse (*Peromyscus oreas* Bangs), deer mouse (*Peromyscus maniculatus* Wagner), southern red-backed vole (*Clethrionomys gapperi* Vigors), creeping vole (*Microtus oregoni* Bachman), Trowbridge's shrew (*Sorex trowbribgii* Baird), montane shrew (*Sorex monticolus* Merriam), wandering shrew (*Sorex vagrans* Baird), and shrew-mole (*Neurotrichus gibbsii* Baird). Each stage under each strategy was ranked for each species as −1 (usually absent), 0 (usually present, but not abundant), or +1 (usually abundant) based on Carey and Johnson (1995). The scores were summed by stage and divided by the score for the managerially fully functional stage to provide a percentage fully-functional forest floor–an index of the biotic function of the foundation for the ecosystem.

An Index of Ecological Productivity–The arboreal rodent community in Washington is unique in that all its members are consumers primarily of the fruits of the ecosystem. The flying squirrel specializes on the fruiting bodies of fungi on the forest floor (plus lichens in the winter); the Douglas' squirrel (*Tamiasciurus douglasii* Bachman) is a specialist on conifer seed; Townsend's chipmunk (*Tamias townsendii* Bachman) consumes conifer seed, fruits and nuts of understory shrubs and trees, and fungal fruiting bodies (Carey 1995). Thus, the abundance of these squirrels is a measure of the reproductive performance of the primary producers in the ecosystem. We used predictive equations for carrying capacities on the Olympic Peninsula (Carey 1995) to calculate density and multiplied density by mean body mass for each species and summed biomass over species. We divided stage biomass by the maximum biomass (managerially fully functional) to obtain an index to ecological productivity (% potential carrying capacity for arboreal rodents). The biomass of arboreal rodents is a measure of the carrying capacity of a forest for predators such as large owls and mustelids.

Carrying Capacities for Deer and Elk–The HABSIM model (Raedeke and Lehmkuhl 1986) was used to calculate carrying capacities for deer and elk under the three types management. Peak densities (83 deer and 34 elk/km^2) were found in the ecosystem initiation stage. Lowest densities (16 deer and 8 elk/km^2) were in the competitive exclusion stage; LSF had intermediate values (39 deer and 13 elk/km^2). We summed values for deer and elk over the landscape by multiplying average values for seral stages by average areas in those stages for the last 200 years of simulations.

Strategies for Managing Stream Sides

A strategy for managing riparian zones is integral to any landscape management effort (Reeves et al. 1995). Rivers, streams, and other wetlands are necessary for persistence of aquatic and amphibian species in forested environments. Both resident and anadromous fish are dependent on healthy rivers and streams. A conservative review by Brown (1985) revealed 11 species of vertebrates besides fish occur only in forested stream side ecosystems (including springs and seeps) (Table 4). Other species use both upland and stream side forests; full reviews are provided by Oakley et al. (1985), Riparian Habitat Technical Committee (1985), and FEMAT (1993).

We adapted two existing riparian management strategies to our simulations, FEMAT (1993) and WFPB minimum requirements (Table 5). Concerns about degradation of riparian ecosystems, anadromous fish, aquatic wildlife, and terrestrial wildlife that use riparian areas led FEMAT (1993) to recommend wide interim buffers on large, medium, and small streams on federal lands (Table 5). We developed a FEMAT-like riparian reserve regime (hereafter referred to as wide buffers). Uncertainty about the utility of wide buffers, and lack of empirically demonstrated value, led the WFPB to require only narrow buffers and only on large, fish-bearing streams, despite the recommendation of its Riparian Habitat Technical Committee (1985).

TABLE 5. Washington Forest Practices Board (WFPB) stream types, nominal widths (m), and amounts in the Clallam River Planning Area (km) and riparian management zone widths (m) and riparian area reserved by WFPB minimum requirements, wide buffers, and a variable-width management zone.

WFPB stream type	Stream width (m)	Amount (km)	Slope distance from stream centerline[a]		
			WFPB	Wide	Variable
1, fish-bearing	30.5	4.2	28.3	123.4	28.3
2, fish-bearing	30.5	16.3	24.1	121.9	24.1
3, fish-bearing	12.2	28.6	17.7	117.3	17.7
4, small permanent	12.2	24.3	0	58.5	9.1
5, intermittent	7.6	188.9	0	29.3	9.1
Area reserved (ha)	n/a	n/a	443	2911	985[b]

[a] Our interpretation on how such guidelines would be applied in Washington; interpretations may differ; guidelines may evolve; WFPB and Wide were interpreted as no-harvest buffers.

[b] About 214 ha of forest are reserved (Type 4 and 5), rest available for thinning.

We thought that wide buffers would provide substantial biodiversity benefits over narrow buffers. In an exploratory analysis (Table 6) to maximize npv with a constraint that 30% of the landscape had to be maintained in late-seral forest (enough to support 1-2 pairs of spotted owls), we found wide buffers:

1. removed 40% of the land from active management and reduced harvestable volumes accordingly;
2. delayed the development of stream side late-seral forest by 70 years more than CBD management, because conifers and coarse woody debris were lacking in existing stream sides;
3. caused more land to be placed under CBD management to meet constraints for late-seral forest early in the simulation and eventually exceeding our goal for late-seral forest;
4. arranged late-seral forest linearly and highly fragmented by competitive exclusion stage forest;
5. resulted in upland areas being managed under very short rotations to mAximize npv; and
6. thus, provided fewer benefits to conservation of biodiversity than we expected–fragmented late-seral forest intermixed with competitive-exclusion forest is detrimental to spotted owls (Carey et al. 1992).

Timber-fiber production with narrow buffers maintained < 3% of the landscape in late-seral forest and 90% in the undesirable competitive exclusion stages. Combining CBD with narrow buffers achieved late-seral forest

TABLE 6. Total volume (10^3 m^3) of wood harvested, percentage of landscape in late-seral forest (LSF) and competitive exclusion stages (CES), and time (yr) to attainment of 30% of the landscape in LSF under management for timber production with Washington Forest Practices Board minimum riparian buffers (WFPB), for timber with wide buffers emphasizing large streams, for biodiversity with WFPB, and biodiversity with wide buffers for a 300-year simulation, Clallam River Planning Area, Washington.

Landscape management upland, riparian	Total harvest	LSF	CES	Time
Timber production, WFPB	135.6	< 3	90	never
Timber production, wide	84.7	35	54	240
Biodiversity, WFPB	144.1	38	8	120
Biodiversity, wide	93.2	56	7	190

constraints well, but did not protect small streams at all. Thus, we developed a third alternative, adapted from Olympic Experimental Forest planners. The planners had delineated riparian zones of varying widths around Type 1-4 streams. Width varied according to soil and slope stability; minimum widths are in Table 5. Riparian zones were extended to incorporate mass-wasting areas. We defined these as no-clearcutting zones but allowed intermediate cuttings under CBD. In addition, we placed a 9-m no-disturbance buffer around Type 5 streams. We called this the variable-zone system.

Simulating Management of a Small Landscape

Assumptions–As are typical of nonreserved, commercial forest land on the Olympic Peninsula (Henderson et al. 1989, Carey 1995, Carey and Johnson 1995), we assumed sites to have low to moderate slope and elevation, moderate productivity (King site index = 105), average soil development, and commonly occurring amounts of coarse woody debris, litter, humus, and other dead organic matter. We assumed sites had few old-growth legacies (Carey 1995, Carey and Johnson 1995). These assumptions implied that commercial thinnings could accelerate forest development over no-manipulations regimes, but that niche diversification and fully functional stages could not be achieved without management for coarse woody debris and cavity-trees (Table 7). We used DNRIMPS to model growth and yield for up to 150 years from ecosystem initiation under various treatment regimes (Table 1). In our final simulations, we assumed (1) all trees were western hemlock, except when Douglas-fir was planted; (2) all new stands began with 1,729 trees/ha with an average dbh of 7 cm at 15 years; (3) precommercial thinning at 15 years left 741 trees/ha; (4) stands adjacent to clearcuttings could be harvested only after 10 years had passed; and (5) variable-density commercial thinnings reduced tree density successively to 247, 178, and 89 trees/ha by year 100. Culmination of mean annual increment of growth was 90 years. New research (Curtis 1995) suggests that all commonly used growth and yield models for coastal Douglas-fir underestimate the culmination of mean annual increment, especially when thinnings are applied repeatedly to stands. Our models probably underestimate culmination age, too. Culmination age varies with site index (productivity), but is older for poorer sites and probably is ≥ 100-120 years for most sites (Curtis and Carey 1996). Thus, wood production under CBD was certainly underestimated. We assumed that maintaining 30% of the landscape (2,040 ha) in late-seral forest would support one pair of spotted owls (which require 1,862 ha/pair, Holthausen et al. 1995), provide nesting opportunities for marbled murrelets, and otherwise benefit organisms associated with late-seral forest. Long rotations (≥ 120 yr) under the biodiversity pathway would provide the time for interactions among ecosystem components to occur, for example those that produce foraging habitat for spotted owls and those that lead to high-quality logs (Table 3). Finally, we assumed that all stands allowed to develop for ≥ 250 years would develop into managerially fully functional or old growth. We chose a planning horizon of 300 years and simulated activities on a decadal basis.

TABLE 7. Stages and substages of ecosystem development and silvicultural treatments of western hemlock forests under management strategies of protection, timber production, and conservation of biodiversity.

	Management strategy[a]		
Period (10 yr)	Protection	Timber	Biodiversity
1	EIS-1	EIS-1	EIS-1 PDF
2	EIS-2	EIS-2 PCT	EIS-2 PCT @ 15 yr
3	CES-1	CES-3	URS-2 VDT @ 30 yr
4	CES-2	CES-4 CC	DUS-1
5	CES-3	EIS-1	DUS-2 CWDT @ 50 yr
6	CES-4	EIS-2 PCT	NDS-1
7	CES-5	CES-3	NDS-2 CWDT @ 70 yr
8	CES-6	CES-4 CC	NDS-4
9	URS-1	EIS-1	NDS-5
10	URS-2	EIS-2 PCT	NDS-6
11	DUS-1	CES-3	FFS
12	DUS-2	CES-4 CC	FFS
13	DUS-3	EIS-1	FFS CC
14	DUS-4	EIS-2 PCT	EIS-1 PDF
15 . . .	BDS 1 . . .	CES-3 . . .	EIS-2 PCT @ 15 yr . . .
25	OG	BDS-1	FFS

[a] Stages: ecosystem initiation, competitive exclusion, understory reinitiation, developed understory, botanically diverse, niche diversification, fully functional, old growth. Treatments: planting Douglas-fir, precommercial thinning, variable-density thinning, VDT with snag and log creation, clearcutting.

Perhaps our most unrealistic assumption was that no catastrophic disturbance (wildfire, windstorm, insect infestation, disease epidemic) would disrupt the forests during the 300-year period. This assumption seems particularly unrealistic for NMP that began with clearcutting-regenerated, closed-canopy, competitive exclusion stages (77% of our landscape) and for windstorms. A similarly potentially unrealistic assumption was that clearcutting-regenerated western hemlock stands will grow, if untreated, into late-seral forest, with its structural and compositional complexity, without the biological legacies left after natural catastrophic disturbances.

Simulations–We incorporated our management pathways, stages and substages of forest development, and growth and yield data and Clallam River Planning Area data on stand conditions, roads, streams, and landscape units into SNAP-II. SNAP-II assigned each landscape unit to 1 of 38 substages of forest development for each simulation decade. Different management strategies produced different sequences of substages and stages; not all substages nor all stages developed in a particular pathway (Table 7). Management strategies differed, then, in both stages that developed and in the time that was required to move from one stage to another. For final simulations of landscape development, we combined one ecosystem management strategy with one riparian management strategy to simulate four landscape management strategies. For each simulation, we set constraints: percentage of the landscape to be maintained in particular stages; a continuous, consistent flow of wood products; and maximizing net present value after constraints were met.

All simulations reflected what a land manager would do given certain discrete goals, constraints, knowledge of market conditions, and a near-term profit (npv) motive. Constraints forbidding manipulation in the NMP simulation made markets, profits, and npv moot in that simulation. Simulations for TFP with WFPB minimum riparian protection had no late-seral forest goals but no timber harvests were allowed within riparian buffers. When TFP was combined with wide buffers there was a constraint of not removing more than 30% of the landscape from production and a late-seral forest goal of 30%, with no timber harvests allowed in riparian buffers; the remainder of the landscape was managed to maximize npv. The most constraints were placed on CBD: 30% of the landscape in late-seral forests, no disturbance within 9 m of small streams, no clearcutting in riparian zones; 70-year rotations had to be followed by >130-year rotations and vice versa under regulation.

Simulated commercial harvest of trees was limited to trees ≥15-cm dbh and to 10-cm tops for thinning and to ≥18-cm-dbh trees for clearcutting. Minimum commercial rotation (harvest) age was set to 40 years; in some simulations, some stands were cut at 35 years to meet multiple constraints as best as possible. Harvests were generally at 50 years, the age of maximum npv. Maximum clearcutting size was limited to 162 ha, but this maximum was never reached; even with minimum riparian protection, about 60% of clearcuttings were less than 24 ha. In adapting the Clallam River landscape units to our simulations, a few large units were retained–these resulted in some clearcuts being larger than would normally result from our management guidelines.

We conducted a series of exploratory simulations using mixtures of strategies, 0-3 thinnings to various densities and at various intervals, a variety of rotation ages, different levels of riparian protection, and constraints of 15% and 30% fully functional forest. Our exploratory simulations were designed to help us understand (1) how our simulator would respond to changes in each variable alone and in conjunction with changes in other variables (an informal sensitivity analysis); (2) where we needed to refine our concepts and questions; (3) how the interactions among tactics influence net present value and landscape arrangement; and (4) in a common way, the unstated goals and assumptions of the various members of the interdisciplinary team. Exploratory analyses helped promote good interdisciplinary communication. We compared conventional silvicultural regimes (with one precommercial thinning, one commercial thinning at 30 or 40 yr, and final harvest at 40-50 yr) to other alternatives, but we found that conventional thinnings were of less npv than CBD variable-density thinnings because greater volumes of wood were removed under CBD and, in the absence of biodiversity objectives, a rational manager would liquidate the entire stand immediately anyway. Because we made simplifying assumptions and modeled silvicultural regimes that have not been practiced, *we caution that the absolute values we report are not as meaningful as the relative differences among the scenarios.*

The Model and Its Assumptions–SNAP-II was designed to assist planners in the scheduling of harvest units. The model (1) identifies efficient harvesting and road access systems, (2) tracks growth in timber, (3) controls the maximum area that can be given specific silvicultural treatments at any one time, (4) controls the maximum area in specified seral stages, (5) provides certain kinds of connectivity across the landscape, and (6) incorporates riparian reserve strategies. The model allows no harvest in riparian reserves. Certain other activities can be proscribed in other landscape polygons, i.e., our variable riparian zone polygons. The program uses a rule-based algorithm to reach timber volume targets specified by the planner; the only costs and benefits that are considered are timber revenues (logging revenues) minus harvest and planting costs. Thus, we set goals for amounts of certain seral stages by listing them as constraints and SNAP-II maximized npv from the remaining area by efficiently scheduling harvests. Net present value is defined in the model as the discounted sum of timber revenues less harvesting, transportation, road construction, and other costs. We used a 5% discount rate and chose not to use price and cost inflators. We used inflation-adjusted 1992 dollars for costs and values. The model calculates timber volume in thousands of board feet (mbf). Stumpage prices varied from < $100/mbf to almost $400/mbf for western hemlock and $450-580/mbf for Douglas-fir, depending on dbh. One board foot is a piece of lumber 1-foot square and 1 inch thick; nominally, 1,000 board feet (mbf) equals 23.6 m^3 of timber. We converted mbf/ac to m^3/ha for this paper by dividing by 9.55, but we caution the reader that, because of complex yield equations, no direct metric conversion exists for mbf–the relationship varies with tree size. We set log values at mill at $316-372 for 30-year old timber and $431-482 for 110-year old timber (with premiums of $69-144 for large logs). Clallam River planners provided us with road costs; Lippke et al. (1996) developed contemporary harvest costs by logging system and analyzed price, cost, and risk assumptions.

Each polygon that was to receive a treatment was linked to either a potential or existing road system and to one to three harvesting systems (ground skidding, skyline, and helicopter). We limited harvest systems to skyline and helicopter in areas of potentially unstable slopes and in variable riparian zones.

Comparing Alternative Landscape Management Scenarios–We evaluated the costs and benefits of our various landscape management strategies after 300 years of simulated management. We incorporated into SNAP-II indices that we developed for values commonly mentioned in public debates about forest land management:

1. net present value of timber revenues to the landowner;
2. economic sustainability of local communities (flow of wood products underregulation);
3. elative value of the landscapes for recreational hunting;
4. ecological function of the forest floor;
5. ecological productivity and carrying capacity for predators;
6. the capacity of the landscape to support all forest vertebrates indigenous to the region.

RESULTS

We learned different things from each of the 3 phases of our study–model construction, exploratory simulations, and simulations of final scenarios. We discuss each in turn.

Model Construction

Our review of wildlife-habitat relationships suggested there were no differences in the development of ecological function as wildlife habitat among second-growth ecosystems in the first 40 years under TFP and NMP. All entered the ecosystem initiation stage after clearcutting and quickly moved to the competitive exclusion stage and stayed there until harvest or until about 90 years (Table 7). Ecosystems managed intentionally for biodiversity quickly gained ecological advantages over those managed under TFP or NMP (Figures 1-3). Protection, however, eventually produced a landscape composed completely of late-seral stages. No species of vertebrates appeared unique to TFP; 14 were unique to CBD and late-seral stages under NMP. Up to 25 species (Table 4) could be at risk in landscapes managed strictly for maximum npv of wood products (TFP-WFPB, Table 8).

No manipulation (NMP) required ≥180 years to cover 30% of the landscape with late-seral forests (Table 9) because numerous habitat elements were missing in the early stages of forest development following clearcutting (Table 3). Early stages had low biodiversity values (Table 10, Figures 1-3). The protected landscape moved through periods dominated by single stages because the initial landscape was relatively homogeneous (Figure 4). Timber pathways produced only 2 stages, ecosystem initiation and competitive exclusion. Competitive exclusion was the least diverse stage–forest-floor function was only 12% of potential, ecological productivity was 19% of potential, and only 64% of vertebrates were provided habitat, with no habitat for 14 upland-forest species (Table 10, Figures 1-3).

FIGURE 1. The capacities of stages of ecosystem development under timber management and protection without manipulation (TFP-NMP) and under biodiversity management (BMP) to support the vertebrates of the western Olympic Peninsula. Seral stages are ecosystem initiation (EIS), competitive exclusion (CES), understory reinitiation (URS), developed understory (DUS), niche diversification (NDS), and managerially fully functional forest (FFS).

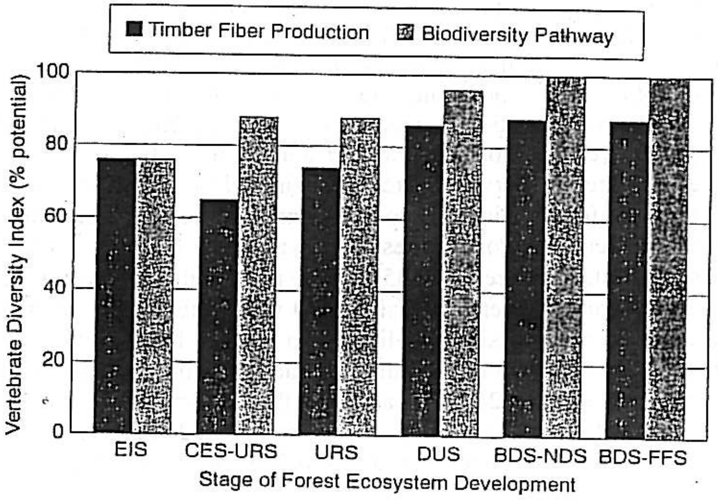
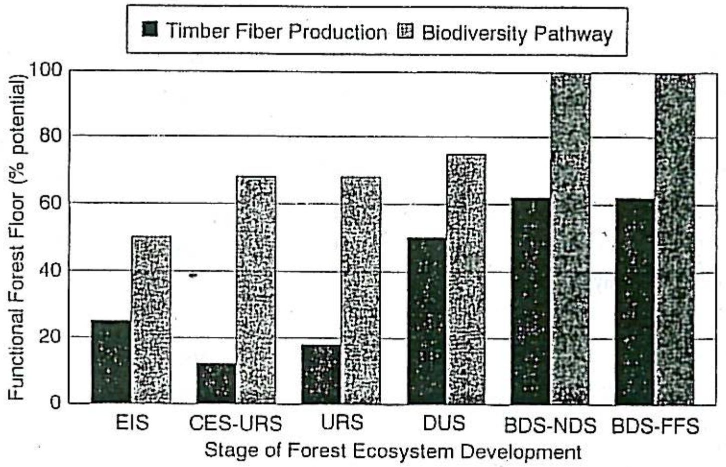


FIGURE 2. The potential of stages of ecosystem development under timber management and protection without manipulation (TFP-NMP) and under biodiversity management (BMP) to support a fully-functional forest floor on the western Olympic Peninsula, as defined by the integrity of the forest-floor mammal community. Seral stages are ecosystem initiation (EIS), competitive exclusion (CES), understory reinitiation (URS), developed understory (DUS), niche diversification (NDS), and managerially fully functional forest (FFS).

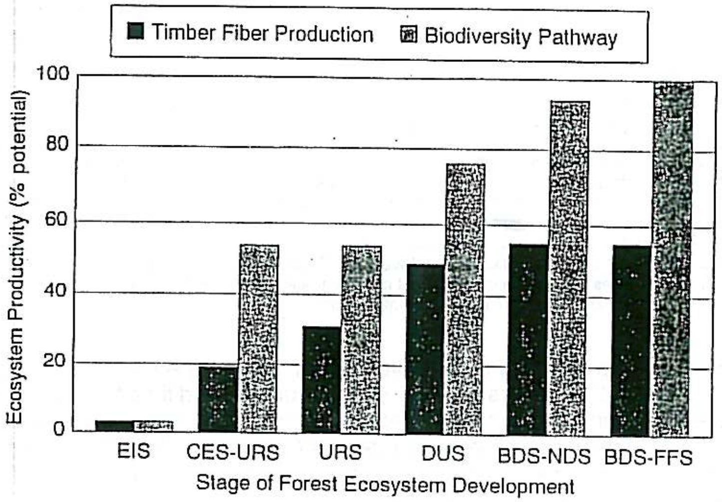


Biodiversity pathways achieved 98% of the potential ecosystem health and also produced a larger variety, higher quality (greater dbh), and, sometimes, greater volume of wood products than TFP (Table 1). Biodiversity pathways had less npv than TFP (Table 1, Table 8), but the reader should keep in mind that: (1) the pathway included both Douglas-fir and western hemlock (Douglas-fir grows faster and is more valuable), (2) the timber-fiber pathways did not contain Douglas-fir because our best understanding was that Douglas-fir was not commonly planted on the bulk of commercial forest of the western peninsula (but could be), and thus (3) comparing mixed-species production to single-species production is somewhat akin to comparing apples and oranges, especially when planting of Douglas-fir is common in other areas of western Washington.

Exploratory Landscape Management Scenarios

We learned five things that conditioned our choice of final alternatives. First, just protecting the landscape was a poor approach to ecological restoration–the entire landscape, in wave-like fashion, passed through the competitive exclusion stage (then understory reinitiation and developed understory stages) before reaching a late-seral forest condition, a process that took ≥ 180 years to obtain 30% late-seral forest, whereas only 100-120 years were required under management for biodiversity (Figure 4).

FIGURE 3. The ecological productivity of stages of ecosystem development under timber management and protection without manipulation (TFP-NMP) and under biodiversity management (BMP) as measured by hypothetical carrying capacities for arboreal rodents. Seral stages are ecosystem initiation (EIS), competitive exclusion (CES), understory reinitiation (URS), developed understory (DUS), niche diversification (NDS), and managerially fully functional forest (FFS).



Second, wide riparian buffers took up >35% of the landscape, eliminating options for managing biodiversity given a constraint of ≤ 30% the landscape removed from production or managed on long rotations as late-seral forest (Table 6). Relying on wide buffers took 240 years to reach the late-seral forest goal. The remainder of the landscape, then, was managed for timber production with short rotations with large, negative impacts on landscape-level biodiversity, including the production of both economic and ecologic goods and services (Tables 8 and 10). Late-seral forest resulting from riparian management was highly linear and fragmented by ecosystem initiation and competitive exclusion stages–these reserves were essentially edges (Figure 5). Streambanks provided edges within edges. We had additional concerns about relying on riparian buffers to provide late-seral forest. We assumed that

TABLE 8. Wood production and timber net present values (npv) produced under alternative landscape management scenarios combining one of three riparian management strategies with 3 upland forest management strategies, Clallam River Landscape, Washington.

Scenario	Upland strategy[a]	Riparian strategy[b]	Npv ($1000)	Volume (10^3 m^3)
NMP	Protect entire landscape	n/a	0	0
TFP	Max npv, PCT15, CC50	WFPB	70,373	161
	Npv, PCT15, CC50	Wide	48,500	111
	Npv, PCT15, CC50	Variable	60,558	136
CBD	Max biodiversity, 130 and 70 yr rotations	Variable	57,930	149

[a] Maximize npv–maximize net present value from timber, precommercial thin at 15 yr (PCT15), clearcut at 50 yr (CC50), minimal riparian protections (WFPB); option for wide buffers and variable-width riparian zones. Maximize biodiversity–plant Douglas-fir; PCT15, variable-density thinning, coarse woody debris and cavity augmentation, and alternating rotation lengths, and variable-width riparian management zones.

[b] WFPB = Washington Forest Practices Board minimum riparian protection standards; Wide = wide no entry buffers patterned after the Forest Ecosystem Management Assessment Team's (1993) interim direction; Variable = narrow riparian management zones that allow intermediate, but not final, timber harvests and active management to restore conifers and that protect mass-wasting areas and headwater streams.

TABLE 9. Mean percentages of Clallam River Planning Area in various seral stages for the last 200 years of a 300-year simulation and time to achieve 30% late-seral forest under alternative strategies for protection (NMP), timber management (TFP) with three riparian strategies (wide, variable, and Washington Forest Practices Board minimum standards, WFPB), and biodiversity (CBD) with variable-width riparian zones.

Management alternative[a]	Ecosystem initiation	Competitive exclusion	Understory reinitiation	Developed understory	Late-seral forest[b]	Time to 30% late-seral
NMP	0	0	0	47	53	180
TFP-wide	28	41	0	14	17	240
NMP-variable	33	49	0	8	10	never
TFP-WFPB	39	58	0	1	2	never
CBD-variable	11	0	11	26	52	80

[a] NMP: protection, no manipulation; TFP: maximize net present value with precommercial thinning and clearcutting at age 50 years; CBD: conservation of biodiversity emphasizing sustainable joint production of ecological services and economic goods.

[b] Goal is 30% late seral forest (20% niche diversification, 10% fully functional steps).

riparian areas were fully stocked with conifers, but, in reality, they had high densities of alder and few conifers. Lack of conifers for stability, habitat, and coarse woody debris recruitment could defeat the purpose of the reserves. Protection of mass-wasting areas was not an integral part of the wide buffer systems. In contrast, variable riparian zones and mass-wasting areas were 17.7% of the landscape, reached late-seral forest condition in 100 years, and were managed for growth of large conifers.

TABLE 10. Summary values (% of potential) and number of species unique to timber management pathways (TF), biodiversity management (CBD), and riparian areas (rivers and streams only).

Biodiversity score	TFP	CBD	Riparian
Unique species	0	14	11
Vertebrate diversity			
minimum	64	75	40
maximum	87	100	65
mode (predominant)	64	100	65
Forest-floor function			not rated
minimum	12	50	—
maximum	62	100	—
mode (predominant)	12	100	—
Ecological productivity			not rated
minimum	3	3	—
maximum	55	100	—
mode (predominant)	19	94	—
Ecosystem health (mode as % potential)	32	98	not rated

Third, biodiversity thinnings were more profitable than conventional thinnings. This result was unexpected, but should have been obvious. Biodiversity thinnings removed more wood than conventional thinnings at a given age (30 years); later biodiversity thinnings removed higher quality wood than early thinnings. Costs accrued to CBD as rotation age was extended and as thinnings removed more wood than necessary to maximize tree growth (one purpose of biodiversity thinnings was to shunt energy in the form of sunlight to organisms besides trees). Conventional thinnings actually resulted in an insignificant loss of npv. Net present value was highest for short rotations without thinnings because of costs of thinning and the time-value of money, despite lack of culmination of mean annual increment of wood production and reduction in total wood produced over time.

Fourth, we found that if we did not managed the landscape as a shifting, steady-state mosaic, attempts to maximize npv resulted in marked 50-year

FIGURE 4. Changes in the seral stage composition of the Clallam River Landscape under (a) protection with no manipulation; (b) protection of streams with wide riparian buffers and management of uplands for timber; and (c) management for maximizing biodiversity. Seral stages are ecosystem initiation (EIS), competitive exclusion (CES), understory reinitiation (URS), developed understory (DUS), niche diversification (NDS), and managerially fully functional forest (FFS).

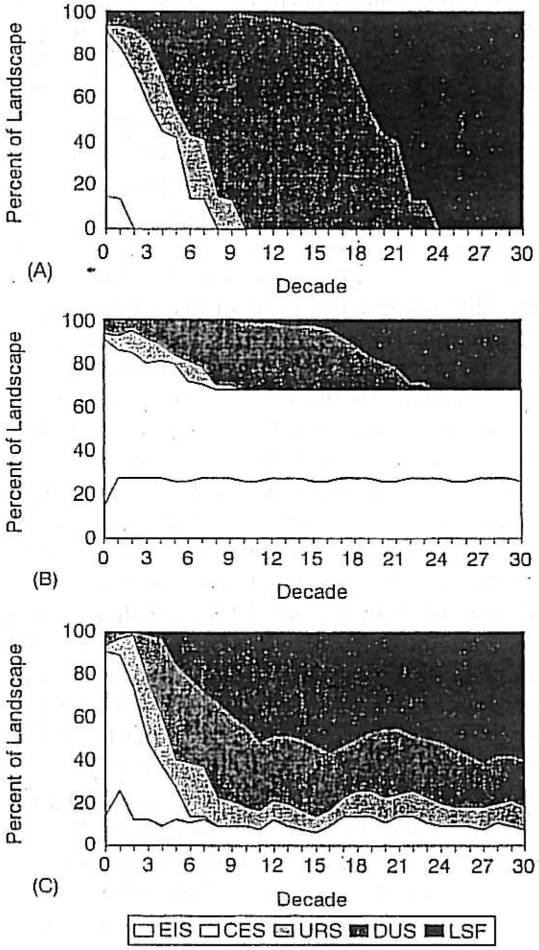


FIGURE 5. Seral stage arrangement and composition of the Clallam River Planning Area after regulation and 300 years of simulated management for (a) timber production with minimal riparian protection; (b) timber production with wide buffers emphasizing small streams; (c) biodiversity with a 30% late-seral forest goal, using a mix a timber management and biodiversity management and variable riparian management zones; (d) maximum biodiversity using a mix of 70- and 130-year rotations with biodiversity management and variable riparian management zones. Seral stage categories are ecosystem initiation (EIS), competitive exclusion (CES), understory reinitiation and development (URS-DUS), and late-seral forest (LSF: niche diversification and managerially fully functional forest).

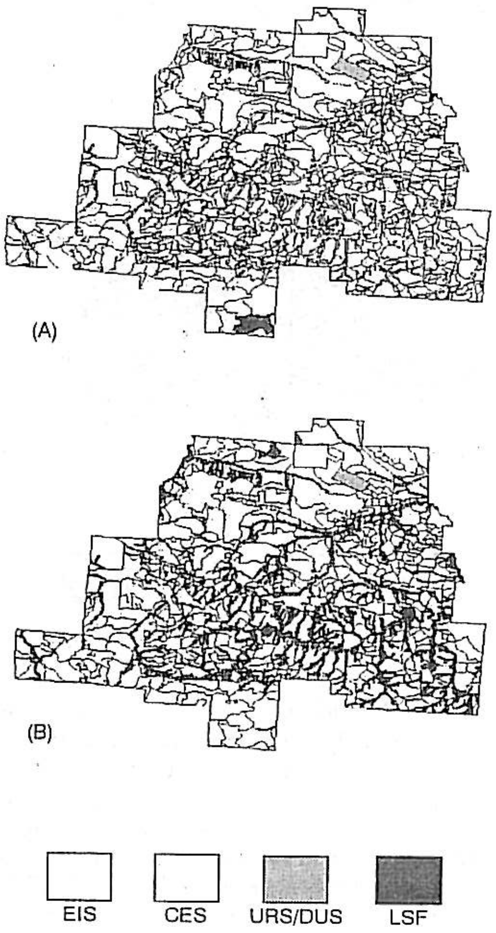
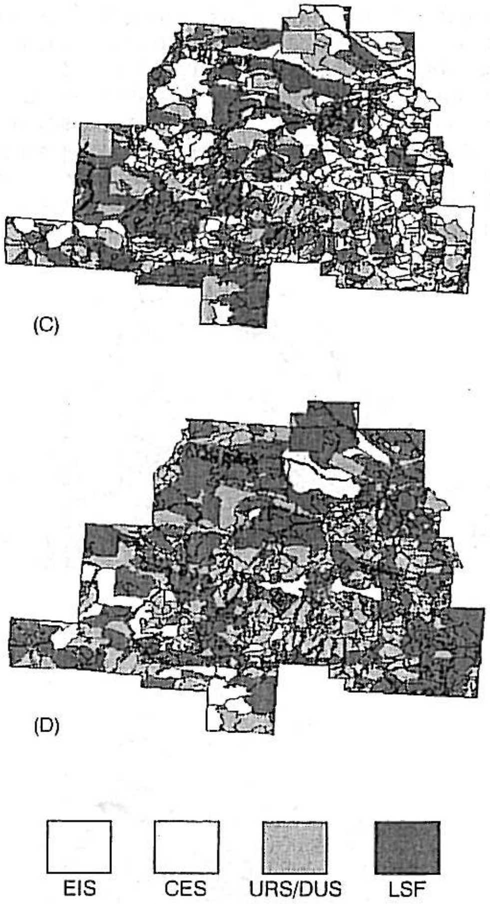


FIGURE 5 (continued)



cycles (in peaks of ecosystem initiation stages and, subsequently, competitive exclusion stages), with five-fold fluctuation in decadal harvests (16,000-72,000 m^3 under TFP and 0-53,000 m^3 under CBD). Under TFP, ecological impacts were especially severe, with ecosystem initiation stages and competitive exclusion stages ranging from 65% to 88% of the landscape during the last 100 years of simulation. Cycles in timber production could be hypothesized to cause temporal ecological bottlenecks (Seagle et al. 1987) in the landscape and, presumably economic constrictions in nearby communities and infrastructure restrictions in the managing organization. We deemed these cyclic impacts unacceptable strove for a regulated landscape, with lowest harvest levels within 10-20% of the trend level.

Finally, homogeneity in seral stage composition of the initial landscape (a condition prevalent in the Pacific Northwest) resulted in substantial costs in bringing the forest into regulation to provide a sustained flow of wood products and ecological services. The small area of the Clallam River Landscape also made it difficult to obtain an even flow of products. Economics limited our ability to rapidly convert the landscape to a desirable structure: the quicker the conversion, the higher the costs. For example, the costs (loss in npv) of converting a 40-80-year old stand to CBD were large because the present value of the stumpage was high; converting a stand to CBD at harvest was low (for rotations of >100 years, costs were near zero). The generalizable costs of CBD, therefore, were calculated on a per-hectare basis assuming initiation of management just after a final harvest or at the time of first thinning, major decision points for managers. But in any case, landscape conversion took a long time (>100 years). With the number of variables used by SNAP-II, variability in the actual Clallam River Landscape, and the small size of the landscape, precisely achieving late-seral forest goals with combinations of silvicultural prescriptions and riparian management regimes was challenging. If we obtained 30-40% cover of late-seral forest under regulation, we claimed success. Given the heuristic nature of this exercise, we decided achieving goals with a great deal of precision did not warrant the effort and fine-tuning that would be required. Thus, our final late-seral forest value with CBD management was 52% of the landscape (Table 10), substantially greater than our minimum requirement of 30%. When we did exceed 30%, it was late in the simulation and had little effect on npv (Table 11).

Contrasting development of late-seral forest with loss in npv provided insight on the cost effectiveness of alternative landscape management regimes (Table 11). Many alternatives met the 30% late-seral forest goal but differed in the amount of late-seral forest maintained. Loss for each 10% gain in late-seral forest varied from \$333/ha under CBD to \$1,035/ha for wide riparian reserves under TFP. Alternatives varied in how quickly 30% late-seral forest was obtained. Timing influenced cost, e.g., delaying implementation of CBD for one decade reduced cost from \$524/ha to \$321/ha.

Initial inventory of seral stages influenced cost. Initially, competitive exclusion stages were over-represented in the landscape. To maximize npv, most of this excess was rapidly liquidated. Under management for biodiversity, some excess inventory was deferred from harvest to meet the late-seral forest goal quickly without inducing oscillations in seral-stage composition. Approximately 50% of loss in npv resulted from reduced liquidation of

TABLE 11. Loss in net present value (NPV) of timber sales, percentage of the landscape in late-seral forest (LSF) after 300 years of management, and the cost ($/ha) for each 10% gain in LSF under various combinations of management solely for timber (TFP) or management for biodiversity (CBD).

Strategy Upland	 Riparian[a]	NPV loss ($ million)	LSF (%)	LSF ($/ha)
TFP	WFPB	0	3	n/a
TFP	Wide	21.9	31	1035
TFP	Variable	9.8	18	798
CBD	Variable	12.5	55	333

[a] WFPB: Washington Forest Practices Board minimum requirements. Wide: wide buffer emphasizing large streams. Variable riparian management zones emphasize management of mass-wasting areas and protection of the banks of small streams.

competitive exclusion stages. Thus, costs of managing for biodiversity included interaction between initial conditions and rate of change.

Final Scenarios

The best solution to a sustained flow of ecological products (species and ecosystem health) and economic products was CBD (Table 8). But significant costs in npv accrued to the landowner.

Wood and Revenue Production–On a stand level, over 100 years and two TFP rotations, CBD produced 1.3% less wood than TFP (Table 1). At rotation age, TFP produced 36-cm dbh trees; CBD produced 76-cm dbh trees. Thus, CBD produced nearly the same volume, but higher quality wood, as maximizing npv with TFP (Table 1). On a landscape, 300-year basis, CBD including riparian and mass-wasting zone management produced only 7.5% less wood than maximizing npv with little riparian, and no mass-wasting, protection (Table 8). Net present value of timber produced under CBD was 82% of maximum npv. Adding effective conservation of riparian values and mass-wasting areas to TFP resulted in a 14% loss in npv, compared to the 18% total loss for maximizing biodiversity. Thus, given effective riparian management, maximizing biodiversity incurred a cost of only 4% of maximum npv. Wide buffers under TFP reduced npv by 31%. Riparian protection with wide buffers was much greater than with variable riparian zones when uplands were managed with TFP (short rotations). Wide buffers, however, did not protect mass-wasting areas or rehabilitate riparian zones through active management.

Harvest Patterns–All strategies resulted in rapid declines in harvest volumes over the first 50 years of simulation as the forest was brought into regulation. Maximizing npv produced modal, decadal harvests in the last 200 years of about 50,000 m^3, a total 300-year harvest volume of 1.6 million m^3, and decadal incomes of $24-28 million. Maximizing biodiversity produced modal, decadal harvests of 48,700 m^3 (a 3% reduction), a total harvest of 1.4 million m^3 (a 13% reduction reflecting riparian and mass-wasting area management), but decadal revenues of $37-47 million, 154-168% higher than maximizing npv, reflecting higher quality wood products. Maximizing npv was not only at the expense of other aspects of biodiversity, but also at the expense of long-term sustained timber revenues (and economic activity in the wood products industry based on an array of wood products and consequent regional economic activity).

Landscape Patterns–Rotation age and management strategy determined landscape pattern (Table 9). Long rotations resulted in 72% fewer clearcuts/decade. Biodiversity management minimized or eliminated competitive exclusion stages. Change from ecosystem initiation and competitive exclusion stages to late-seral forest was accelerated by management for biodiversity (Figure 4). Maximizing npv with TFP produced a landscape dominated by competitive exclusion, and secondarily by ecosystem initiation. During the last 200 years of simulation, only 2% of the landscape was maintained in late-seral forest, all of which was in patches < 24 ha. Accordingly, 38% of the landscape was in ecosystem initiation stages, with 89% in patches > 24 ha, too large to be of optimum value for deer and elk. Under our assumptions, wide no-harvest buffers eventually developed into late-seral forest in corridors dominated by adjacent competitive exclusion and ecosystem initiation stages (Figure 5). With wide buffers, an average of 17% of the landscape was in patches of late-seral forest > 24 ha. Landscapes produced by maximizing biodiversity (Figure 5) had 50% of the landscape in patches of late-seral forest >24 ha and 2% in patches of late-seral forest < 24 ha, separated primarily by developed understory stages. Only 11% of the landscape was in ecosystem initiation stages with 45% of clearcuts in patches < 24 ha.

Ecological Values–The competitive exclusion stage had the lowest values of all stages for vertebrate diversity, forest-floor function, ecological productivity (Figures 1-3), and production of deer and elk. Maximizing npv required short rotations and no commercial thinnings that also maximized the proportion of the landscape in competitive exclusion stages. Large proportions of the landscape were repeatedly subjected to clearcutting followed by three decades of competitive exclusion that produced severe ecological impacts (Table 9, Figure 6c). Ecological productivity and forest-floor function were maintained at < 22% of potential. Vertebrate diversity was maintained at 70% of potential. The timber-fiber production pathways did not provide any habitat for 14 species of vertebrates. Current WFPB buffers used in conjunction with timber-fiber production did not provide any protection to small streams and only minimal protection to large streams; another 11 species would not find hospitable environments in landscapes managed for maximum npv (Tables 3, 9, and 10). Wide riparian reserves with TFP in the uplands produced better results, but still well below the potential of the landscape. Management to maximize biodiversity captured > 90% of the capacity of the landscape to support vertebrate diversity, about 80% of the potential forest-floor function, and almost 70% of ecological productivity (Figure 6). Biodiversity pathways provided habitat for all forest vertebrates, with variable riparian zones providing protection to small streams and seeps that support riparian species most sensitive to forest management (Table 4). Management for biodiversity, with its legacy retention, coarse woody debris and cavity-tree management, and variable-density thinnings provided stages with maximum values and a landscape with minimal variance in values and no human-induced ecological bottlenecks. Disturbances that were induced (clearcuts) were limited in time and space when compared to management under TFP or long periods in competitive exclusion and understory reinitiation under NMP. When ecological indices are considered simultaneously, maximization of npv provided 32% of potential biodiversity, management for biodiversity provided 98% of potential (Table 10).

In exploratory scenarios with TFP, deer populations averaged 290 (range of 200-400) and elk averaged 123 (80-175). With biodiversity constraints of 30% fully functional forest, deer populations were slightly higher, averaging 305-317, and elk were much higher, averaging 157-170. The average number of deer that would be harvested was 73 when npv of timber was maximized and 77-80 when TFP was balanced with 30% fully functional forest. Average number of harvested elk was 31 and 42, respectively. Maintaining late-seral forest and reducing competitive exclusion stages had positive effects on ungulate populations, especially elk. In the final scenarios, we estimated that the average populations in Clallam River Landscape over the last 200 years of simulation would be 423 deer and 134 elk when net present value of timber was maximized and 401 deer (slightly lower) and 200 elk (markedly higher) when biodiversity was maximized.

DISCUSSION

Caveats

Our analyses were carried out making numerous assumptions, both ecological and economic. We recognize that predictive ability in both sciences is poor. But, we modeled only what we considered common conditions. We

FIGURE 6. Changes in biodiversity indices (capacity to support vertebrate diversity, forest-floor function, and ecological productivity) for the Clallam River Landscape with: (a) protection only; (b) wide riparian buffers with timber management in uplands; (c) timber management with minimal riparian protection; and (d) management for maximizing biodiversity.

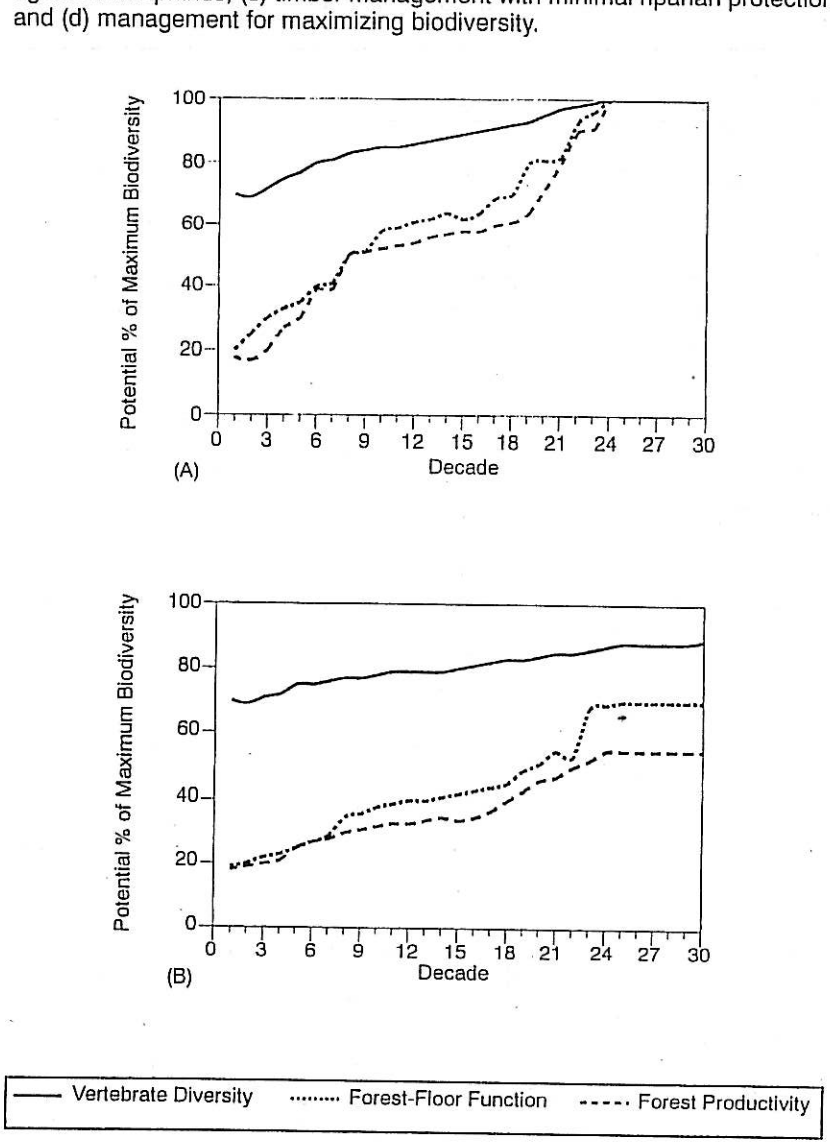
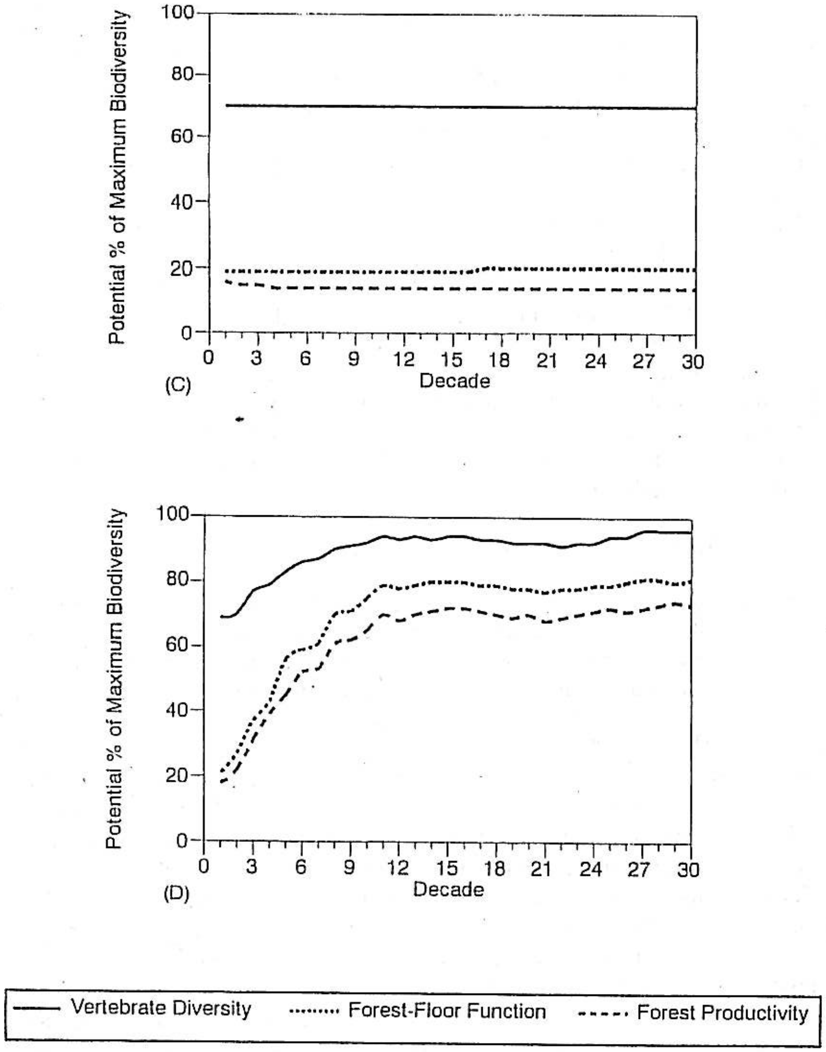


FIGURE 6 (continued)



believe we were conservative in estimating the ecological values of management for biodiversity. Incorporating more of the common lands of relatively low timber productivity in the model would make conservation of biodiversity even less expensive. Age of culmination of mean annual increment is older on these lands. Adoption of variable riparian management zones as the WFPB minimum standard would make conservation of biodiversity less expensive. Improved growth and yield models would make conservation of biodiversity less expensive (and we did not model ingrowth by shade-tolerant species). All together, conservation of biodiversity would incur costs of < 3% of net present value. Our economic analyses, however, are meant only to give broad, relative estimates. Nevertheless, the initial landscape conditions (distribution of area among seral stages) and other landscape-specific characteristics (e.g., distance to markets) make extrapolations to other landscapes allowable only on a "general principles" basis. The principles of conservation of biodiversity are fully applicable to other areas of the Pacific Northwest, as are the seral stages (e.g., Carey and Kershner 1996). The biodiversity management pathways and ecological evaluations, however, were specific to the western Olympic Peninsula and would require fine-tuning to local conditions before use in simulations elsewhere in the Pacific Northwest.

We constructed timber production pathways narrowly; however, many managers are beginning to incorporate some management for biodiversity for sustainability and for public relations. We wanted to separate methods traditionally used for timber management from methods used to conserve biodiversity. The state of science is not good enough to model all the gains and losses that might accrue or be incurred across a continuum from management solely for wood production to management solely for preservation of species.

Our purpose was not to make precise predictions about the future, or to replace Clallam River planners, but rather to (1) present a framework for planning and analysis, (2) illustrate pathways for management, and (3) illustrate the magnitude (not absolute values) of the costs of remedying imbalances in seral-stage distribution and of conserving biodiversity in the future. We also developed and applied some novel indices to ecosystem and landscape function that demonstrate how ecosystem management could be evaluated. These indices are hypotheses that are being tested experimentally. We concentrated on upland systems and were weak on aquatic systems. We emphasized measures of ecological integrity over species occurrences. Adding evaluation criteria for aquatic systems would be challenging, but worthwhile. Landscape maps, however, suggested that riparian health would be maximized under management for biodiversity compared to the other alternatives we considered.

The environmental sustainability of the strategy for maximizing net present value given the ecological and economic bottlenecks we identified is questionable. We do not know enough to assess the impacts on long-term site productivity, but the ecological indices suggest loss of function. Likewise, we have not evaluated the impacts of continued manipulation of forest ecosystems under the biodiversity pathways, especially impacts from soil compaction or loss of productivity caused by maintaining a proportion of the forest in well-maintained roads. The impacts of repeated thinnings are being studied in experiments and early results show rapid recovery from variable-density thinning (Carey et al. 1996b). The recent exploration of "kinder, gentler" European thinning machinery on the Olympic Peninsula proffers optimism.

Finally, the development of indices of ecosystem and landscape function, through controlled experimentation, will not only produce indices of known relevance and reliability, but also will provide managers with a tool for monitoring and feedback processes for adaptive management. In the Forest Ecosystem Study (Carey et al. 1996b), a variety of measurements are being tested, including: measures of soil food webs, measures of ectomycorrhizal fungal fruiting activity, the diversity of fungi that bear fruit above ground, fungal diversity in flying squirrel diets, the composition, abundance, diversity, and growth rates of vascular plants; the integrity and abundance of the forest-floor small mammal community, and the abundance of the arboreal rodent community. All these items being measured are related to trophic pathways, maintenance of diversity in trophic pathways at the levels of decomposers, primary producers, consumers, and, ultimately, predators, and, thus, to ecological integrity. But we do not yet have enough knowledge to model all the communities composing the trophic pathways and their response to alternative management regimes.

Offsetting some weaknesses in our modeling, were the strengths in baseline data on the function of Pacific Northwest forests in providing wildlife habitat and producing timber. Systematic, replicated studies of plant, amphibian, bird, and mammal communities had been conducted in young, mature, and old-growth forests (Ruggiero et al. 1991). Similarly, studies of spotted owls had been replicated geographically (Thomas et al. 1990, Carey et al. 1992). The ecology of forest-floor mammals and arboreal rodents in relation to vegetation structure and composition and biological legacies had been compared regionally (Carey 1995, Carey and Johnson 1995). Relationships between seral stages and fungal production and effects of silvicultural treatments on key biotic communities had been studied (Luoma 1991, Carey 1995, Carey et al. 1996b). Substantial information on growth and yield of western hemlock and Douglas-fir under various conditions was available (Curtis and Carey 1996).

Conclusions from Our Modeling

There is great potential for conserving biodiversity in managed landscapes without maintaining large upland or wide riparian reserves. Long (>120 years) rotations are required on significant proportions of the landscape. Intensive management (plantings, precommercial thinnings, and commercial, variable-density thinnings) is necessary. Mixing goals and management pathways is practical and could lead to recovery of some threatened species and maintenance of populations of sensitive species and game animals. Conserving biodiversity with a mixture of long- and short-rotation biodiversity pathways is even more effective economically and ecologically. Moving toward a regulated shifting, steady-state forest mosaic is highly desirable and probably necessary for general sustainability. Management techniques for biodiversity, such as riparian reserves and biodiversity pathways, can conflict, with unintended negative consequences for timber production and for rate at which biodiversity goals are met. Because (1) late-seral constraints were relatively low (20% niche diversification and 10% fully functional), (2) biodiversity pathways contribute to producing economically valuable forest products in both the short term and on a sustainable basis, and (3) biodiversity pathways can achieve many of the goals of reserves, management across land ownerships on large watershed bases appears practical. Management of large areas for maximization of net present value through timber and fiber production without consideration for biodiversity raises questions about sustainability and endangering additional species.

Ecological Approaches to Landscape Management

Our landscape was dominated at the outset by competitive exclusion stages, loss of coarse woody and forest-floor organic matter, and degraded riparian systems. We focused on restoration of landscape function for biodiversity. Our goal was to move from a state of ecosystemic degradation due to cultural abuse to a healthy natural/cultural landscape mosaic, not a fully natural state (Regier 1993).

We developed and modeled alternative strategies for managing ecological communities and alternative scenarios for managing small landscapes incorporating (1) minima for late seral forest, (2) strategies for riparian protection, and (3) tactics for enhancing biodiversity (balancing steady state vs. cyclic production; short vs. medium vs. long rotations; legacy retention and planting vs. intensive site preparation and natural seeding; and biodiversity management pathways vs. timber management pathways vs. no manipulation). Biodiversity management was not simplistic alternative thinning regimes. Careful consideration was given to the requirements of different life forms, ecosystem processes, and empirically measured spatial variation in canopy cover and understory vegetation (Carey et al. 1996a).

Although our emphasis has been on activities in landscape units (ecosystems or stands), we have shown how management pathways, riparian management, and attempting to enhance biodiversity have significant implications at the small landscape (and larger) spatial scales. Active management and rotation age can interact to produce a range of landscape conditions from fragmented late-seral forest with dominance by early seral stages to continuous late-seral forest with a virtual absence of the least diverse competitive exclusion stage. Steady-state constraints and rotation age interact to produce a shifting mosaic of late-seral forest with a sustainable flow of ecological and economic goods and services. The absence of a steady-state constraint produces severe bottlenecks.

We are not suggesting that primeval forest in the Pacific Northwest existed as a shifting, steady-state mosaic; it did not. Rather, the forests were influenced by large-scale catastrophic disturbances including fire, volcanos, and glaciation (Agee 1991, Brubaker 1991). The most persistent seral stage, however, was old-growth, taking > 200 years to develop and lasting 100-500 years in much of western Washington. Nor do we suggest that land managers should try to recreate historic landscape conditions; because there was no steady state, these conditions varied markedly from century to century. Rather, under our strategy of conservation of biodiversity, we suggest managers attempt to maintain a regulated, dynamic mosaic that meets diverse human needs on a time schedule that appears reasonable based on empirical retrospective documentation of forest development; these needs range from wood products to waste assimilation (e.g., carbon sequestration) to recreational opportunities to the knowledge that the landscapes maintain all species of indigenous wildlife. Indeed, a concept of general sustainability seems to be emerging as part of a new cultural movement (Carey 1998).

We have illustrated that the arrangement of biotic communities in space (including riparian management zones) and the structure of the landscape (composition and arrangement of seral stages) through time determine connectivity and landscape function. For example, landscape composition determines the ease with which organisms can move through the landscape. Changes through time (pathways) and landscape composition determine the ease with which a local population can persist though time, as does harvest pattern and the resulting matrix of stand conditions in more traditional management, as shown by Franklin and Formann (1987) and Franklin (1993). There are other approaches to landscape management that might be less efficacious, as effective, or perhaps more effective, depending upon the initial conditions of the landscapes. Landscapes dominated by naturally originated late-seral forests have more potential for conserving species diversity in the short-term, and perhaps in the long-term, than landscapes that have been through severe, human-induced ecological impacts. The former landscapes have a greater storehouse of biological legacies and species diversity.

We had substantial empirical documentation of wildlife-habitat relationships and forest structure, composition, and development. The habitat relationships of many species of invertebrates, fungi, and lower plants, however, were unknown. Our current state of knowledge and experience led us to a modeling approach based on comparative empiricism, a kind of hybrid between the holistic perception of an informed naturalist and the analytic understanding of an abstract scientist, i.e., a pragmatic synthesis devoid, we hope, of band-wagon paradigms (Regier 1993). This approach incorporates the concepts of biological integrity and ecosystem health explicit in Leopold's land ethic but is disparate from Pinchot's consumption-oriented resources conservation ethic (greatest good for the greatest number for the longest time) and Muir's preservation ethic, wherein spiritual needs take precedence over material needs (Karr 1993). This notion of ecosystem integrity is rooted not only in certain ecological concepts but also in certain sets of human values wherein the relevant normative goal of human-environmental relationships is to maintain the integrity of a combined natural/cultural ecosystem that expresses both ecological understanding and an ethic that guides the search for proper relationships (Regier 1993).

We concluded that a forest intentionally managed as a regulated, shifting, steady-state mosaic of ecologically desirable seral stages–the natural/cultural landscape mosaic of Regier (1993), not the naturally occurring steady-state mosaic described by Bormann and Likens (1979), would be more likely to produce a mix of ecological and economic benefits characteristic of a strategy of conservation of biodiversity than a strategy of aggregated timber harvests with legacy retention (Wallin et al. 1994).

Sustainable Forestry–Forests throughout the world have been destroyed by wasteful and short-sighted forestry practices. Indeed, there has been a "remarkable consistency in the history of resource exploitation: resources are inevitably over-exploited, often to the point of collapse" (Ludwig et al. 1993:17). The causes of overexploitation are that wealth begets political power, biological and physical complexity precludes simplistic approaches to management; large levels of natural variability can mask the effects of overexploitation until they are severe and, often, irreversible; and scientific consensus is hampered by lack of experimental controls and replication in research (Ludwig et al. 1993).

Today, economists warn that excessive protection of forests in developed countries could shift demand for wood products to third-world countries, which have less productive forests and less environmental regulation, even though the U.S. has more forest under management today than any time in the past 50 years (Oliver and Larson 1996). Just as reducing timber harvests to preserve forest ecosystems in first-world countries can lead theoretically to increased harvests and reductions in biodiversity in third-world countries, short rotations (regeneration harvests prior to culmination of mean annual increment) in first-world countries would have the same effect by not effectively harnessing the productive capacity of the land and by not providing the full range in quality of wood products. Thus, inefficient use of productive forest land to maximize short-term profits could have increasingly severe impacts on global biodiversity as populations and demand for all forest products increase.

It is interesting that efficient use is often assumed to be short-rotation management–an assumption that is not true from the standpoints of (1) culmination of mean annual increment (maximizing total wood production over time); (2) substituting harvest of wood products through thinning for suppression mortality; (3) producing high-quality and high-valued wood products; (4) maintaining long-term forest productivity; and (5) conserving biodiversity, the capacity of forest ecosystems to meet the needs and desires of future generations.

Achieving Scientific Consensus–Ehrlich and Daily (1993) add political pressures and yearning for public attention to legitimate scientific concerns as reasons for lack of consensus among scientists. To these must be added preferences for cognitive style (Carey 1998), personal belief systems (Ludwig 1993), culture (Regier 1993), and the less palatable greed (Lee 1993b), or self-service. Of course, these impediments to scientific consensus are also impediments to political consensus. In any case, scientific consensus is unlikely, and by definition in science, ephemeral if achieved at all.

Discount Rates–Much of the debate over future forest management on state and private lands will incorporate effects on net present value, the use of positive discount rates, and who should bear the cost of moving away from management based on net present value. Discount rates, along with growth and yield assumptions, have been a prime driver of forest management practices in the past. However one must reflect on how much the real-world manager relies on simplistic net-present-value calculations (as opposed to relying on disciplinary dogma, Ludwig 1993) in making management decisions. Should (do) the federal forester, native American tribal forester, state forester, community-based corporate forester, family-corporation forester, family-farm forester, and national-international corporate forester all base all decisions on net present value? In addition to sustainability, many land owners and managers must consider (or choose to consider) a variety of values from amenities to public relations (citizenship) to other investments (for example, a pulp mill).

Future-looking corporate managers, worldwide, stress quality of working life and productive workplace communities (Weisbord 1994). The productive workplace community is an anchor point for dignity and meaning in democratic societies. Quality of working life can be a serious effort to conserve our culture's deepest values against erosion by narrow economic and technocratic thinking. Preserving economic stability beyond quarterly dividends (net present value) is important because democratic societies depend on creating employment (Weisbord 1994). Lippke et al. (1996) showed employment can be more than doubled by management for biodiversity. Quality of working life, productive workplace communities, and dignity and meaning in work are all enhanced by the knowledge that the work is contributing to the greater economic community and society in general. Quality of working life for natural resources professionals and technicians can not be divorced from the quality of the natural environment and the health of forest-based human communities. Effective long-term management of natural resources must be, according to Weisbord (1994), pragmatic, moral, humanistic, ethical, economic, technical, and social if people are to find meaning and dignity in work.

At another extreme, Lee (1993a:194) asserts that "positive discount rates . . . transfer resources from future generations to those now living . . . [and] shifting of economic benefits to the present . . . can be justified only if economic growth continues." Thus, with finite area and resources, the only viable route to sustainability is to stop economic growth and work toward zero-discount rates. Thus, "property rights that induce lasting husbandry are an essential component of any policy of sustainability."

Regardless of the opportunities to manage for non-timber goals and community-based economic stability, if timber owners receive less return than other investments of equal risk, forest management capital may be diverted away from management for biodiversity to other, more profitable, alternatives. Lippke et al. (1996) illustrated how institutions could provide incentives to efficiently produce both the ecologic and economic benefits that accrue from management for biodiversity. Johnson (1995) provides an overview of incentives that might be appropriate for implementing our biodiversity pathways on private lands. In addition to tax reforms, conservation easements, and long-term management permits, financial and technical assistance, educational outreach, expanded forestry incentive programs, and other programs hold promise.

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