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NEW FORESTRY PRINCIPLES FROM ECOSYSTEM ANALYSIS OF PACIFIC NORTHWEST FORESTS[1,2]

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Abstract. Forest management practices on Federal lands in the Pacific Northwest of the United States have been the center of intense controversy, Conflicting value systems, new information, and new perspectives have fueled the debate over the balance between timber production and preservation of natural ecosystems. In this paper we consider examples from three aspects of forest management: (1) management of forest stands, (2) management of the patchwork of forest stands at the landscape scale, and (3) management of streams and riparian networks. In each of these cases we examine: management practices and perspectives of the recent past, findings from ecosystem research that are leading to change in those practices, resulting changes in management practices, and future research directions. We also suggest a path for future change, including systems for managing in the face of uncertainty.

Results of research in natural and managed forest and stream ecosystems have been pivotal in reassessment and redesign of management practices to provide a broader range of management options for society to consider. Results of studies of natural disturbance processes and their effects are used as reference points for management systems intending to sustain biological diversity and ecosystem productivity. Stand management practices, for example, are being modified to retain some live trees and greater amounts of dead woody debris, both standing and down, in areas that would instead be clear-cut under intensive plantation forestry practices. The motivations for these modified practices are to sustain biological diversity, including key wildlife species, and to maintain soil productivity. Models of alternative forest-cutting patterns at a landscape scale are being used to examine their effects on ecosystem structure and function. One result of this analysis has been to shift from the previous system of dispersing cutting units to a system involving greater aggregation of units using designs to provide for species preferring forest interior habitat as well as species favoring edge and early sera1 habitats. As a result of ecosystem research, the management of stream and riparian networks can now be based on understanding of forest–stream interactions and designed within a drainage-basin context. Overall, emphasis in research and management seems to be in early stages of shifting from featured species- e.g., Douglas-fir *(Pseudotsuga rnenziesii* (Mirb.) Franco) and Northern Spotted Owl *(Strix occidentalis caurina)*- to ecosystems, and from the scale of forest stands to landscapes and the entire region.

In addition to the contributions of ecosystem research to redesign of management techniques, ecosystem scientists also have roles in the social processes for determining the future course of management of natural resources. An important medium for scientist participation is establishment of adaptive management programs, in which management activities are conducted as experiments to test hypotheses and to develop information needed for future natural resource management.

Key words: biological diversity; commodity vs. environmental objectives; conservation biology; forest ecology; forest management; forest site productivity; landscape ecology; Pacific Northwest forests; riparian zone; stream ecology; stream management; sustainable ecosystem management; watershed management.

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[2]For reprints of this group of papers on forest management, see footnote 1, page 219.

INTRODUCTION

Forestry is undergoing a major transformation in response to social pressures, growing global concern with sustainable management of natural resources, and new knowledge about ecosystems. This transformation is affecting the land management, research, and educational sectors of forest resource management (NRC National Research Council 1990). The reverberating effects of this transformation are perhaps nowhere more pronounced than in the Pacific Northwest of the United States, where intense controversy surrounds the future of multiple-use management and the conversion of natural forests, particularly old growth, to forest plantations. At stake are the major natural resource base of a region, the social fabric and value systems centered on that resource base, and threatened species, such as the Northern Spotted Owl *(Strix occidentalis caurina).*

Ecosystem, wildlife, fisheries, and forestry research (Thomas et al. 1979, Salwasser and Tappeiner 1981, Edmonds 1982, Harris 1984, Salo and Cundy 1987, Franklin 1989, Hunter 1990, Nehlsen et al. 1991) has played a pivotal role in this social transformation. Each of these fields of research has distinctive institutions, dominant research approaches, and major topics of interest, but over the past decade they have overlapped sufficiently to achieve a degree of common understanding of the biology of natural resource systems. In some regions this new knowledge is contributing to changes in traditional management systems that have placed emphasis on single products. The emerging emphasis on integrating management of all natural resource values is consistent with existing legal requirements of federal forest managers, such as protecting species and sustaining productivity.

In the terms of Salwasser (1990), we are experiencing an evolution across three stages of natural resource management, from regulation of uses (focus on avoiding clearly undesirable activities) to sustained yield management (focus on a few desired products) to sustainable ecosystem management (focus on the well-being of the ecosystem, which is providing many goods and services). Early steps in the development of sustainable ecosystem management for forest and stream systems are occurring under several banners, including the USDA Forest Service's “New Perspectives” program (Salwasser 1990, Kessler et al. 1992 [this volume]) and the concepts of “New Forestry” (Franklin 1989). The intent of these programs is to better match management practices with the broad array of human values and philosophies concerning natural resources. In forestry this means balancing commodity and environmental objectives by using practices based on current ecological understanding, the realistic limitations of the resource base, and societal expectations, including those expressed in Federal legislation.

The task of balancing commodity and environmental concerns is difficult because of the complexities of ecosystems and a variety of uncertainties facing natural resource managers. Since ecosystems are so complex and dynamic, managers typically focus on a few key structural and functional features; identification of such features is an important part of changes in forestry. Furthermore, management decisions take place in the face of three major categories of uncertainties: (1) long-term consequences of our present practices in today’s climate, (2) potential effects of changes in the global environment, and (3) change in the social and political setting of forestry. The social and political factors are perhaps the most profound sources of change and uncertainty at this time. To deal with these objectives and uncertainties, land managers need a broader range of tools, both social and technological.

This paper deals with one facet of these broad issues—changes in management practices derived from results of ecosystem research. We draw on examples from research and management in the Douglas-fir forests of the Pacific Northwest, but many of the principles apply in other regions as well. Research findings, policy analysis, and management actions in other regions and countries are clearly important sources of both information and influence affecting change in the Pacific Northwest. The pace of change in policies concerning old-growth forest preservation and species conservation is extremely rapid in the Pacific Northwest. Consequently, research information is being put to new uses rapidly and frequently, changes in land allocations and management policies alter the course of planned management and long-term research, and social, political, and legal factors may overshadow ecosystem science as a base for major decisions. Nevertheless, this region provides valuable examples of the roles of ecosystem research in multiple use management.

Two important considerations of the context of the issues discussed here influence the applicability of new practices and perspectives. First, the rate of resource extraction is ultimately a social and economic decision within certain biological and physical constraints, so technical aspects of changes in management practices do not accomplish the difficult task of deciding the balance between competing management objectives and value systems. Second, the Pacific Northwest of the United States may be rather unusual in (1) its relative wealth of natural ecosystems, (2) a significant level of scientific understanding of those systems, (3) strong links between research and management communities, and (4) modest population pressures. Consequently, this area can be an important testing ground for new ideas, but transfer of those ideas to other areas must be sensitive to differences in cultural, social, and economic settings.

We consider examples from three aspects of forest management: (1) management of forest stands, (2) management of the patchwork of forest stands at the landscape scale, and (3) management of stream and riparian networks. In each of these cases we examine: (1) management practices and perspectives of the recent past, (2) findings from ecosystem research that arc leading to change in those practices, (3) resulting changes in management practices, and (4) future research directions to further improve the foundation for integrated resource management. Finally, we suggest a path for future change, including systems for managing in the face of uncertainty.

FOREST STAND MANAGEMENT

Past perspectives and practice

In the decades of the 1940s through the 1980s forest cutting and much forestry research in the part of the Douglas-fir region considered here (west of the crest of the Cascade Mountains in Washington, Oregon, and California) focused on the harvest of natural stands and establishment of Douglas-fir plantations. This was accomplished with relative efficiency by clear-cutting, burning woody residues on the entire harvested area to reduce wildfire hazard and facilitate planting of seedlings, establishing dense stands of a single crop species, and hastening crown closure by suppressing competing vegetation.

These practices had economic, biological, and even philosophical rationales. Intensive forestry practices were developed to produce a high level of wood fiber and economic return, particularly in the short term. Research and development in support of intensive plantation forestry centered on systems for forest regeneration, suppression of competing vegetation, genetic improvement of planting stock, efficient fertilization, animal-damage control, and other objectives. Some aspects of the resulting practices seemed consistent with prevailing concepts of natural disturbance and successional processes. It was commonly suggested in magazine advertisements, for example, that clear-cutting mimicked wildfire, but clear-cutting was not so wasteful in that the dead wood produced by a management treatment is utilized.

The forests resulting from traditional, intensive plantation forestry in the Douglas-fir region are designed to be structurally and compositionally simpler than natural forests and to substantially reduce the extent of forest age classes older than 100 yr. This has lead to concern and debate over the fates of soil productivity, watershed conditions, and wildlife species that rely significantly on older forest habitat.

Roles of ecosystem research in management changes

Important changes in understanding natural systems have emerged from analysis of the structure and function of natural terrestrial and aquatic ecosystems and their responses to disturbance. Studies of disturbance effects have revealed the dramatic importance of organisms surviving even extremely severe events. This was particularly clear after the 1980 eruptions of Mount St. Helens, where the first impression was of complete eradication of the previous ecosystems. Within days and weeks, however, surviving organisms of various life-forms began the process of restoring terrestrial and aquatic systems (Anderson 1982, Antos and Zobel 1982, Wissmar et al. 1982, del Moral 1983, Franklin et al. 1985). Survivors persisted belowground, in rotten logs, under snowpacks, and in lakes, streams, and springs, some protected under ice and snow cover.

Similarly, studies of wildfire history in Oregon revealed that this dominant disturbance process in the region was more complex than previously recognized. This region had a variable natural fire regime, ranging from one dominated by very long rotation, stand-replacement fires in parts of northwestern Washington to frequent fires of variable intensity in southwestern Oregon (Hemstrom and Franklin 1982, Agee 1990). Many of the fire-history studies in the region have been based on written records and dendrochronologic analysis using increment borings in standing forests, both of which provide a limited view of the possible existence of low- and moderate-severity fires recorded in disrupted tree-ring patterns. Recent studies in the central Cascade Range of Oregon, based on detailed dendrochronologic analysis of fire-scar and total-tree-age records exposed in stumps, revealed that wildfire was more frequent and involved a greater extent of low- and moderate-severity burning than expected (Teensma 1987, Morrison and Swanson 1990). Large, catastrophic fires were very heterogeneous, composed of patches of diverse sizes and bum severity. This complex wildfire regime left abundant standing and down dead woody debris as well as highly variable densities of live trees.

These studies of disturbance regimes and effects highlight the importance of "legacies" of surviving biological structures (e.g., large standing and down logs, soil aggregates), chemical imprints in soils (e.g., high levels of calcium in litter associated with cedar trees [Kiilsgaard et al. 1987]), and propagules (Halpem 1988, 1989) surviving from the predisturbance system. Surviving elements from predisturbance systems can strongly affect the rate and course of ecosystem recovery. Consequently, the design of ecosystem manipulations and prediction of system response must consider the nutrients, organisms, and structures both retained on and removed from a site as a result of disturbance.

Parallel with this disturbance ecology research has been a great deal of study focused on natural forest and stream systems. In the Pacific Northwest much of this work began with the International Biological Program in the 1970s (Edmonds 1982) and is continuing in both large and small research programs sponsored by the National Science Foundation and other institutions. Findings from these studies that are relevant to changes in forest practices include:

1) Standing and down dead woody material provides habitat for many species and is necessary to sustain elements of biological diversity and possibly forest productivity (Larson et al. 1978, Jurgensen et al. 1979, Harmon et al. 1986). Intensive plantation forestry practices greatly reduce concentrations of woody debris on the forest floor after the residual woody debris from the previous natural stands has been disposed of or decomposed (Spies and Cline 1988, Spies et al. 1988).

2) Natural forest stands are very complex in the early and late stages of succession and they contrast with the simpler structure and composition of stands managed intensively for wood fiber production (Franklin et al. 1981, Hansen et al. 1991, Spies and Franklin 1991). Intensive plantation forestry eliminates or reduces the duration of complex early and late seral forest stages (Spies and Cline 1988, Hansen et al. 1991), possibly eliminating wildlife species that are dependent upon them (Brown 1985, Thomas et al. 1990, Ruggerio et al. 1991). Furthermore, intensive but unsuccessful efforts to establish tree plantations on harsh sites may disrupt the belowground ecosystem to the point that the site is converted to nonforest vegetation (Perry et al. 1989).

3) Input of nitrogen to Pacific Northwest conifer forests occurs in part by nitrogen-fixing organisms particularly evident in early and late successional stages of forest development (Pike 1978, Carroll 1980, 1981, Binkley et al. 1982). Intensive plantation forestry may greatly reduce the presence of these species by truncating both early and late seral stages. This can occur with short cutting cycles and the suppression of some vegetation considered to be competing with crop species. The net effect may be a reduction in long-term nitrogen input to forest systems where nitrogen availability commonly limits productivity (Miller et al. 1986).

4) Canopy invertebrates, such as spiders (Schowalter 1988, 1989), ants, and insectivorous birds (Torgersen et al. 1990), can be important predators of forest insect pests. Simplification of forest structure and composition by intensive plantation forestry may shift predator–prey relations. Techniques, such as retention of habitat structures in the form of large, live trees and multiple canopy layers, may be developed to maintain beneficial predator–prey relations in managed forest stands and landscapes.

5) Coarse woody debris in streams increases channel complexity, thereby improving habitat quality and increasing the retention of nutrients in stream systems (Triska and Cromack 1980, Gregory et al. 1991). A variety of past management actions, including stream cleanup practices employed in the 1970s and 1980s greatly reduced levels of coarse woody debris in streams, thereby reducing habitat quality (Bisson et al. 1987).

We could cite many additional examples of ecosystem elements that contrast between natural forest and stands managed intensively for wood fiber production. Considered individually, perhaps none of these ecosystem functions justifies revamping traditional forestry practices. However, considered in aggregate, improved understanding of ecosystem structure and function points to the clear need to modify intensive plantation forestry for use on Federal lands where there is strong legal mandate to sustain productivity and native and desirable non-native species.

Changes in the management of forest stands

The new information derived from ecosystem, forestry, wildlife, and fisheries research, coupled with changing public expectation of forest and stream management, has forced rethinking of forest management over the past decade and especially in the past few years (Harris 1984. Eubanks 1989, Franklin 1989, Franklin et al. 1989, Perry and Maghembe 1989). The basic theme in these revisions of management has been to retain more-natural levels of ecosystem complexity than is accomplished through intensive plantation forestry practices, as developed in the Pacific Northwest. The new concepts include retaining or creating greater amounts of live trees and of dead material, both standing and down, in the cutting units. The objectives include sustaining biological diversity, sustaining long-term site productivity, and possibly mitigating effects of forest cutting on hydrology and soil erosion. Practices aimed at enhancing or maintaining system complexity can be implemented in stands of any history, including initial cutting in natural stands, salvage logging in areas affected by wildfire and windstorm, and pre-commercial and commercial thinnings in plantations. To evaluate the long-term consequences of such management, it is essential to consider management effects over several cutting cycles and in a landscape context.

Where management objectives include both production of wood fiber and sustaining old-growth forest habitat, results of fire history research suggest several alternative management systems. The distinctive attributes of old-growth forests, large live and standing and down dead trees (Franklin et al. 1981), may have been sustained on some sites for many centuries, even through multiple disturbances (Morrison and Swanson 1990). In a partial mimic of this disturbance regime, selective cutting practices could be used to sustain complex stand structure and composition for long periods. Such multi-age management strategy may in many cases be superior to a long-rotation, even-aged management system in which up to two centuries of stand development are required before old-growth characteristics are achieved. The selection of stand management systems should be based in part on the natural disturbance regime of individual sites, in order to accommodate the effects of future natural disturbances as they interact with managed stands.

The extent to which non-traditional forestry practices meet the biological objectives for which they were designed has yet to be determined in detail by research and monitoring. A major theme in using these practices before thoroughly testing them is to maintain future options for ecosystem management; for example, it is easier to leave standing dead trees and large, rotting logs on a site than to generate them from an initially clean clearcut. These modified cutting practices result in cutting units that do not really fit the term "clearcut," which was appropriately applied to cutting units in the recent past.

The concepts and practices of silviculture are evolving rapidly as new objectives are being considered, such as stand management at many stages of stand development to benefit late seral species, including the Northern Spotted Owl. Alternative silvicultural concepts arc being developed and tested in a great variety of forest types and initial stand conditions, including natural stands, plantations, and areas of recent disturbance. Each case requires site-specific prescriptions. Examination of ecological effects of new practices will lead to further changes in practices, to better meet evolving objectives.

Research direction

Two lines of stand-scale research are underway at modest levels in the Pacific Northwest: (1) continued study of the basic ecology of forest stands and (2) operational testing of diverse stand-management systems. Foci of the basic studies include canopy processes, aboveground–belowground nutrient and ecological relations, and species–habitat relations. The operational testing considers silvicultural, wildlife, ecological, social acceptability, economic, and a range of other aspects of alternative silvicultural treatments. We expect that a major effort over the next few decades will focus on the ecology and management of established plantations, where little ecological research has occurred to date.

MANAGEMENT OF THE FOREST PATCHWORK

Landscape patterns in Federal forest lands in the Pacific Northwest are composed of patchworks of forest stands and nonforest vegetation reflecting the history of disturbance and resource availability (Franklin and Forman 1987, Swanson et al. 1990). Management activities influence patterns through forest cutting, efforts to manage the disturbance regime, and designation of various types of reserves (e.g., Wilderness Areas, Research Natural Areas, habitat reserves for single species). Patchwork dynamics also involve forest succession and the natural disturbance regime, which interact with the landscape structure created by management activities. In the following discussion we focus only on cutting patterns, but the issue of landscape management ultimately includes design of riparian networks (see *Stream and riparian systems,* below), systems of reserve areas, interactions between management-created landscape patterns and natural disturbances, transportation systems, and other factors.

Past perspectives and practices

From the 1940s through the 1980s forest cutting on Federal land in the Douglas-fir region was accomplished with dispersed cutting units of ≈15 ha each. This dispersed cutting regime was used to accomplish a variety of objectives: (1) to rapidly develop a road system for fire protection and other forest management activities, (2) to facilitate regeneration by seed fall from adjacent stands, (3) to disperse the hydrologic and sediment production effects of cutting over watersheds and through time, (4) to create edge and early seral habitat for game species in an otherwise continuously forested landscape, (5) to minimize the visual effects of clear-cut areas, and (6) to use a management system distinctive from the practices on private lands, where progressive clear-cutting of large areas was widely employed.

By 1990, with ≈30% of the Federal forest land (excluding Wilderness Areas) in the Pacific Northwest converted to plantations, many of these objectives had been met or superseded. Additional objectives of landscape management had emerged also. The primary road system, for example, was nearly complete in many areas. Regeneration from seed was found to be ineffective, so planting of seedlings became the method of choice. An abundance of edge and early seral habitat had been created; meanwhile attention shifted to species associated with large areas of interior forest habitat. Some of the objectives and associated strategies of previous decades remained relevant, such as dispersing cutting units to minimize cumulative watershed effects. However, these practices are being modified to balance better with newer objectives and strategies.

Role of ecosystem research in changing management

Ecosystem and wildlife research has been pivotal in triggering a rethinking of landscape pattern management. Key research contributions have been: (1) modeling effects of dispersed cutting patterns on disturbance regimes and wildlife habitat (Franklin and Forman 1987), (2) analyzing habitat preferences of multiple species in relation to landscape patterns (Harris 1984), and (3) understanding the ecology (and subsequent listing as threatened) of the Northern Spotted Owl, a species with preference for large blocks of interior old-growth forest habitat in parts of its range (Forsman et al. 1984, Thomas et al. 1990). Here we consider only the first point, using it as an example of

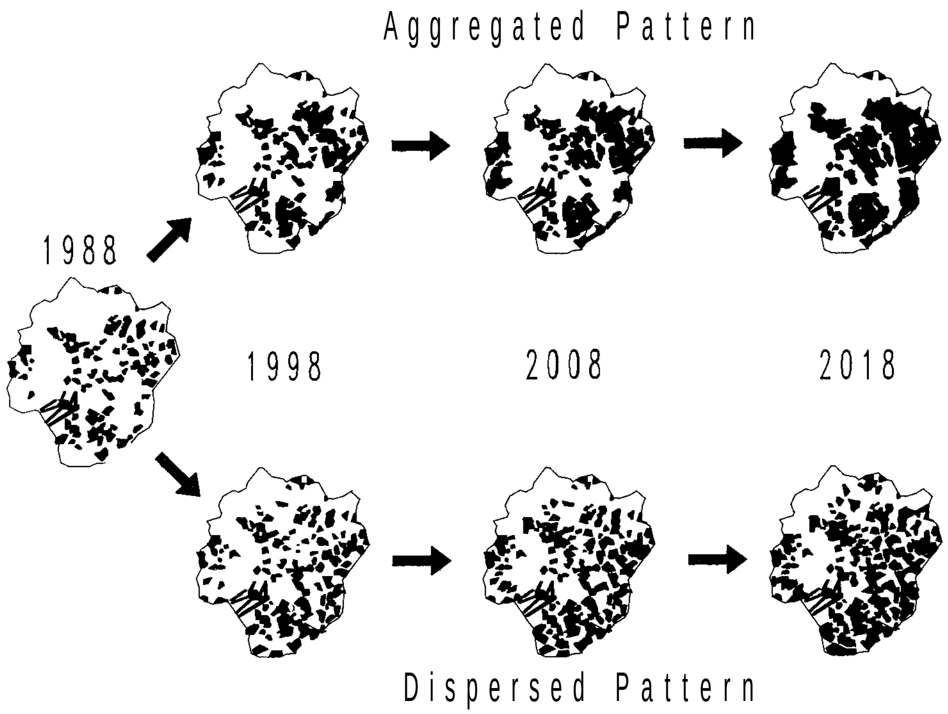

FIG. 1. Pattern of cutting units (dark areas) of ≈15 ha each in the 5000-ha Cook and Quentin Creek drainage basins near Blue River, Oregon. Cutting patterns until 1988 were based on a dispersed cutting system. Dispersed and aggregated cutting patterns are shown for the next three decades. Residual, natural forest is unshaded.

the effect of ecosystem research on management practices.

Franklin and Forman (1987), Li (1989), and Hansen et al. (1992) examined effects of dispersed and several other cutting patterns using simple analysis of a grid system in which grid cells in a forest landscape are cut over a rotation (one cycle of cutting in a landscape area). They observed that in a system with maximum dispersion of cutting units, a 50%-cut landscape has maximum density of edges of natural forest patches. Edge density is likely to be strongly correlated with the potential for disturbance by processes that operate preferentially on forest–nonforest edges. In the 37 000-ha Bull Run River watershed and neighboring area (Mt. Hood National Forest, Oregon), for example, wind blew down 482 and 899 ha of forest in 1973 and 1983, respectively. Franklin and Forman (1987) reported that 48% (1973) and 81% (1983) of the blowdown occurred in forest adjacent to clearcuts.

Creating a landscape composed of dispersed small forest patches and young plantations results in extensive areas affected by altered microclimate at forest edges. The zone of edge influence extends several tree heights into the residual forest (Chen et al. 1991), thereby eliminating some characteristics of interior forest habitat from forest patches even >10 ha. Therefore, some species of wildlife and plants with strong interior-forest microclimatic requirements, such as the nitrogen-fixing canopy lichen *Lobaria oregana,* may be eliminated from a landscape that is only half cut.

Changes in management

In response to concerns about "forest fragmentation" (Hams 1984, Franklin and Forman 1987), some Federal forest managers began to experiment with "minimum fragmentation" cutting patterns in the late 1980s. In this system new cuts are placed adjacent to earlier cuts, rather than in the middle of uncut blocks of natural forest (Hemstrom 1990) (Fig. 1). The objective is to retain relatively large blocks of continuous interior-forest habitat until later in the cutting cycle, and to create greater diversity in the "grain" (dominant elements of the size distribution of forest patches) of the forest patchwork generated by cutting. The simple dispersed cutting system creates a landscape with a 15-ha grain. By accepting more variance of cutting-unit size and of aggregation in the cutting pattern, managers can create more diverse and natural landscapes, which may provide better habitat for the variety of species present.

The concept of designing landscapes for ecological objectives is relatively new and will change as we learn more about many topics, including the effects of different cutting patterns in upland areas on streams and riparian systems. Stream ecologists, for example, are beginning to consider the effects of chronic vs. relatively large-scale, pulsed disturbances in drainage basins. The dispersed cutting system produces chronic disturbance by having fresh cutting units and most of the road system active at all times. Greater aggregation of cutting units will affect associated stream networks in more of a pulsed fashion for some decades, followed by a recovery period of 50 to >100 yr. The appropriate middle ground between these extremes of timing of management activities is now being debated.

The point of these concepts of landscape management is not to switch from one narrow set of management rules (e.g., dispersed cutting) to another (e.g., aggregated cutting), but rather to consider a broader range of approaches to better meet a range of management objectives. In the case of the forest patchwork this may mean a variety of cutting-unit sizes, sizes of aggregates of cutting units, cutting frequency, and distribution of types of silvicultural practices. These approaches should be applied in the context of constraints imposed by topography and the natural disturbance regime.

The major factor influencing the near future of forest landscape management in the Pacific Northwest is management of the Northern Spotted Owl, potentially threatened fish stocks and species, and other species distinguished by the question of their survival or by special use, such as the case of Pacific yew (*Taxus brevifolia* Nutt.), from which a cancer-curing drug is derived. Researchers, managers, and policy-makers are now challenged to develop conservation strategies involving both preserve and commodity lands.

Research direction

Rapid change in landscape management is underway in the Pacific Northwest in response to increased attention to landscape issues; to implementation of geographic information system technology, which provides greater ability to conduct spatial analysis; and to establishment of reserve systems for single species, which raises the question of how other species and land uses may be affected. Continuing studies by researchers and managers clearly point the direction of near-term future research:

1) Long-range modeling of alternative patterns and rates of forest landscape change must be undertaken. In much Federal forest land in the Pacific Northwest, conversion of natural forest to managed forest is only partially complete. To clearly see the long-range, cumulative effects of management practices, it is essential to examine ecosystem properties through the transition rotation and well into the first fully managed rotation, In addition to the degree of aggregation of cutting units, the alternatives considered should include variation in rotation length, size distribution of units, the characteristics of stand-scale practices, and design and management of transportation systems. The need for this analysis is particularly acute now, because the extent and course of conversion of natural to managed stands is being reassessed.

TABLE 1. Existing and prospective elements of forest cutting treatments (land-use designation) at a landscape scale in Forest Service lands in the Pacific Northwest. Spotted Owl habitat conservation areas are proposed in Thomas et al. (1990).

Future cutting	Past cutting: No	Past cutting: Yes
No	Wilderness areas	Spotted owl habitat conservation areas
Yes	Roadless areas where forest cutting may take place	General forest

2) Such models of alternative landscape patterns must be linked with analytical techniques, such as modeling, to evaluate the responses of key variables, such as economic return, streamflow regime, and habitat for species with various habitat ranges and sera1 class requirements.

3) Long-term, landscape-scale field experiments should be established in the framework of "Adaptive Management" (Walters and Holling 1990), using management treatments as experiments. Treatment blocks at the scale 20 000 to >100 000 ha, for example, are actually or prospectively on differing paths of past and future cutting (Table 1). Land-use patterns in the Pacific Northwest are creating landscapes with diverse structures, rates of change, and sensitivities to natural disturbances. Land management setting defines critical time and space scales for analysis, information needs, and constraints on the range of treatments possible. Fisheries issues and territory sizes of wildlife species require that areas possibly exceeding 100 000 ha be considered as treatment units for some research objectives. The rate of landscape treatment (e.g., 1-2% of the area is cut per year in the Pacific Northwest) and the time scale of secondary succession (centuries for forests in the Pacific Northwest) set the minimum time scales for assessment at several centuries.

A variety of study approaches should be used in concert to capitalize on these experimental opportunities: retrospective studies can depict the change in landscape structures and processes to date; synoptic studies of the present condition of study units on differing developmental tracks can reveal effects of differing management histories; design of future management as experiments with follow-up monitoring can be used to test explicit hypotheses derived from retrospective and synoptic studies. Modeling can be used as a medium for synthesis of information drawn from these study approaches. Some use of multiple, coordinated approaches is now underway in the Pacific Northwest, but on a very limited basis.

Stream and Riparian Systems

The riparian zone lies at the sometimes contentious interface between forestry and fisheries management. Riparian zones and associated streams form a network throughout a landscape, serving as both distinctive habitat and as a transportation system for water, sediment, nutrients, and aquatic and terrestrial organisms. The flow of materials is dominantly unidirectional; movement of organisms can be either up- or downstream. We distinguish consideration of the stream/riparian network from the upland patchwork of vegetation, discussed above, because of distinctive attributes of these two types of structures and the associated movement of materials, organisms, and disturbances through them.

Past perspectives and practice

Management of stream and riparian systems has evolved over the past half century with a general trend of increased retention of live trees along streams and large woody debris in channels. Guidelines for doing so generally take the form of targets for width of vegetation zones or numbers of trees and/or debris pieces per unit length of stream channel. Before the 1980s in the Pacific Northwest the primary purpose for leaving trees in streamside areas was for water quality, particularly for control of sedimentation and shading to minimize warming of stream water that might be detrimental to fish. Federal legislation had placed great emphasis on water-quality issues, which in the western United States centered on temperature and sediment. As a result of research in the 1960s and 1970s the water temperature issue seemed rather tractable in terms of predicting response to manipulation of vegetation (Brown 1969). Research on small, experimental watersheds identified major sediment sources, which were considered in the development of best management practices to minimize the sedimentation impacts of forest practices (Fredriksen 1970, Hornbeck and Swank 1992 [this volume]).

Role of ecosystem research in changing management

Ecosystem research in the 1980s focused on the complex array of linkages between forests and stream ecosystems and the geomorphic setting of stream and riparian networks (Swanson et al. 1982, Triska et al. 1982, Gregory et al. 1991). Beginning with analysis of forest–stream linkages within individual study sites and then expanding to consideration of geomorphic controls distributed over drainage networks, this work led to the recognition that simply minimizing management impacts on sedimentation and water temperature issues was inadequate for dealing with management effects on stream and riparian systems. A full ecosystem consideration of habitat structure, food resources for aquatic and terrestrial wildlife, disturbance regimes, and nutrient cycling is needed (Gregory et al. 1991).

The ecological interactions between forests and streams form the basis for a functional definition of riparian zones—the zone of direct interaction between forest and stream systems delimited in terms of ecological functions, such as shading and delivery of fine and coarse organic debris to streams (Fig. 2). Other approaches to definition and delimitation of riparian areas have been based on botanical (e.g., distribution of hydrophytic plants) or hydrologic (e.g., zone of inundation by floods of a particular return period) criteria. Although simple botanic or hydrologic criteria are convenient for delineating riparian zones in legal and land-allocation arenas, management of stream and riparian ecosystems is best accomplished within the framework of a functional definition.

Forests affect streams by regulating the food base and habitat structure of aquatic systems. Forest effects on nutrients and the food base include the regulation of light available for primary production in streams, the direct input of food-base materials to streams in the forms of leachate in throughfall and as detrital material via litterfall, and the biogeochemical processing associated with surface water and groundwater in channel and floodplain areas (Triska et al. 1982, 1989, Gregory et al. 1989, 1991, Lamberti et al. 1989). The structural influences of forests on streams are similarly diverse. Roots in streambanks and large woody debris, ranging in size from single pieces to massive accumulations, form important structures that regulate the movement of water, sediment, and particulate organic matter. These structures create habitat for aquatic organisms and retain particulate organic matter, which is an essential component of the food base. The geomorphic and biologic functions of coarse woody debris in channels have received a great deal of analysis in diverse ecosystems (reviewed in Harmon et al. 1986 and Bisson et al. 1987), with the resounding conclusion that this material is a critical element of stream ecosystems.

It is important to place this functional understanding of forest–stream linkages into drainage basin and geomorphic contexts (Grant et al. 1990, Swanson et al. 1990). We do so in a hierarchical series of structural scales (Gregory et al. 1991) (Fig. 3). Much past stream research and management (e.g., habitat enhancement structures) has focused at the channel units scale (e.g., pools, riffles). However, we find important variation in the stream ecosystem function and forest–stream interactions at the scales of subunits and stream reaches. At the subunit scale of individual eddies and edge habitat features with dimensions less than one channel width, Moore and Gregory (1988a, *b)* observed that more structurally complex sites provided greater habitat for rearing fish fry. Stream reaches (Fig. 3), valley floor areas with lengths of hundreds of metres to many

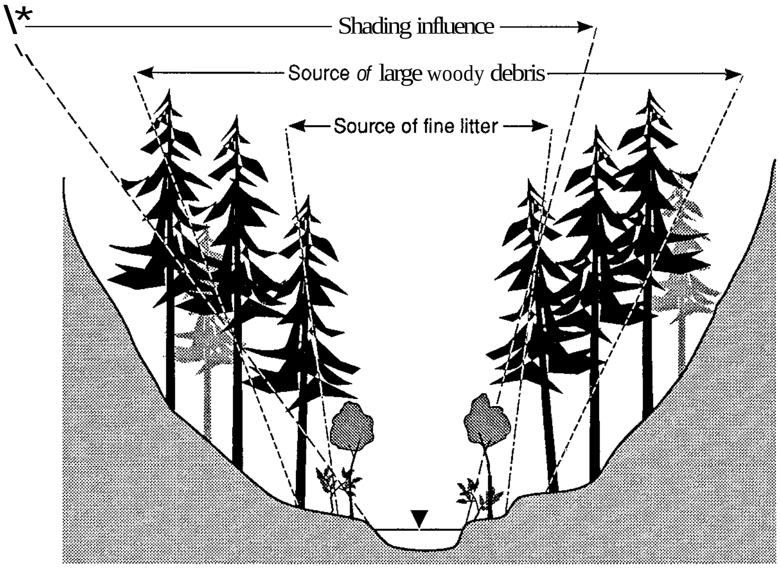

FIG. 2. Schematic cross section of a valley floor and riparian vegetation, showing several of the major ecological effects of forests on stream systems. The asymmetry of the zone of shading influence is intended to represent the dependence of this function on the orientation of the valley floor relative to the solar path.

kilometres, arc distinguished on the basis of type and degree of lateral constraint on valley floor and channel width by geological features, such as bedrock, alluvial fans, and landslide deposits. Several studies of streams in the Cascade Range of Oregon have shown that the wide valley-floor areas of unconstrained reaches have complex histories of lateral channel changes recorded in vegetation and landforms. Consequently, the riparian canopy in unconstrained reaches is relatively open over the stream, resulting in higher light levels in the stream and therefore higher rates of primary and secondary (invertebrate) aquatic production, greater foraging efficiency by fish, and higher standing crop of fish than in relatively constrained reaches (Lamberti et al. 1989, Gregory et al. 1991).

Stream reaches differ in the types and frequencies of geomorphic events involved in the disturbance regimes of reaches. For example, unconstrained reaches have greater potential for lateral channel changes, and therefore have a stronger imprint of fluvial disturbances on the distribution of age classes and the community composition of riparian vegetation. These geomorphic proccsscs affect aquatic systems through both direct modification of channels as well as through influence on vegetation dynamics. For these reasons the stream-reach scale of system structure is an important stratum within stream classification systems used in research and management (e.g., Frissell et al. 1986).

These ecosystem perspectives of drainage basin geomorphology and ecology arc at the stage of a conceptual model, which is codified in part in a general stream ecosystem model (McIntire and Colby 1978 and more recent versions). Some individual components arc represented in additional simulation models (e.g., Van Sickle and Gregory 1990). An important, additional medium for integration and synthesis is the design of riparian management systems extending over full drainage basins and over full cutting cycles, i.e., on the order of >100 yr (Gregory and Ashkenas 1990).

Changes in management

These findings have prompted managers to design specific projects, such as logging and stream habitat enhancement work, with regard for (1) local ecological functions and management objectives; (2) basin context, in terms of location within the drainage network; and (3) geomorphic context, in terms of reach-scale structure, the associated geomorphic and vegetation dynamics, and the diversity of resource values and constraints of reaches of different structure (Gregory and Ashkenas 1990).

An important benefit of using an ecological definition of riparian zones is that it provides a basis for management by objectives, even at the fine scale of an individual tree or pool. For example, if coarse woody debris benefits fish habitat in terms of trapping spawning gravel or forming complex rearing habitat, then wide streamside forests grown for production of large, decay-resistant tree species that will ultimately form coarse woody debris pieces in the channel may best meet the long-term management objective. In other sites consideration of water temperature effects on fish may lead to the desire for development of streamside forests with structure and composition that provide maximum shading.

Basin-scale design considerations include shaping streamside management zones to the valley floor land-

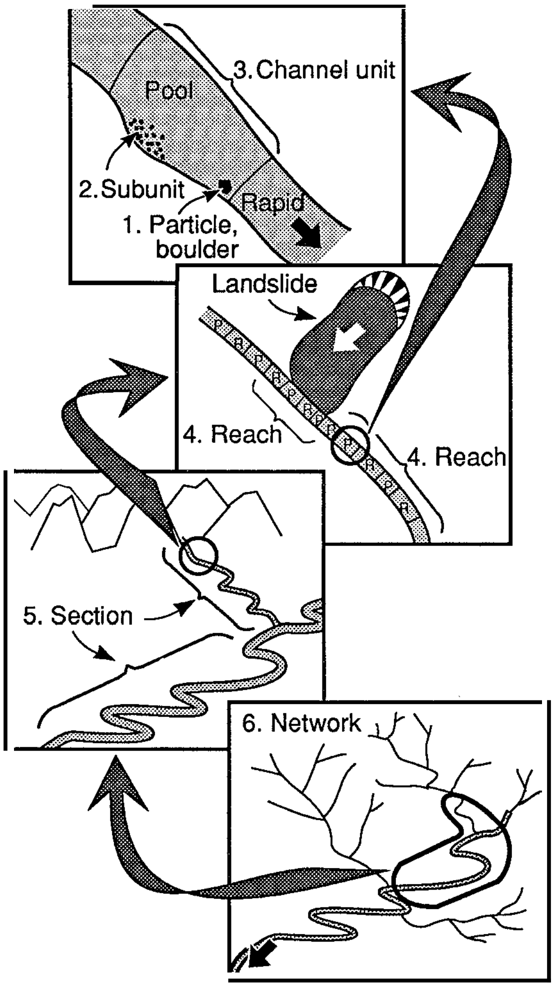

FIG. 3. Hierarchy of valley floor geomorphic structures (redrawn from Swanson et al. 1990). "P" and "R" within the area designated as reaches (scale 4) refer to pool and riffle. "Section" (scale 5) refers to the scale of features, such as high-gradient, mountain river sections or meandering, low-gradient river sections through broad valleys.

forms, with recognition of their long-term disturbance dynamics and channel-floodplain interactions such as those considered in the flood pulse concept of Junk et al. (1989). For example, wider vegetation zones are left in areas of wide valley floor, which have extensive, diverse aquatic and riparian habitat and a tendency for lateral channel change. Narrower buffers are left in areas of rocky gorges, where landforms provide shade and rock outcrops limit lateral channel shifts. The overall intent is to better design stream and riparian systems within their drainage basin context.

Research direction

The next important steps in understanding stream and riparian networks include study of: (1) reach-to-reach interactions in terms of routing of nutrients, sediment, woody debris, and disturbances through drainage basins; (2) long-term dynamics of natural and managed streamside vegetation zones, recognizing how succession and disturbances are likely to affect their structure, composition, and function; (3) the hyporheic zone, where floodplain groundwater derived from the main channel, hillslopes, tributaries, and direct precipitation can interact with floodplain vegetation and soils; and (4) linking the structure of the upland forest patchwork with the stream and riparian network.

SUMMARY AND CONCLUSIONS

Forestry practices in the Pacific Northwest are in a period of major, rapid change as new objectives are merged with results of research. Clearly the process of change is on an evolutionary course—there is not now nor will there ever be a simple set of prescriptions for multiple-use, multiple-value management of complex ecosystems.

The ecosystem research to which we have referred is substantially focused on understanding natural ecosystems and the implications for management systems. This perspective does not constitute a "naturalistic ideology" in the sense of managing ecosystems for the sake of naturalness. Rather the strategy is to use knowledge of natural ecosystems to develop practices of sustainable ecosystem management (Salwasser 1990, Lubchenco et al. 1991). One aspect of this strategy is to minimize the subsidies or investments (e.g., fertilizer, pesticides, investment-intensive silvicultural treatments, stream habitat enhancement structures) necessary to meet management objectives and to buffer society and ecosystems in the face of major uncertainties, such as effects of climate change. An important aspect of sustainable ecosystem management is to maintain future opportunities to manage for ecological objectives.

A major challenge to ecosystem scientists and managers is merging the design of forest stands, landscape patchworks, and stream/riparian networks to produce the most desirable future landscape conditions and levels of productivity. The difficult social aspect of this challenge is to determine those desirable future conditions. These considerations point to the need for new relations between land managers and ecological and natural resource scientists. The critical factor is development of social systems for management of natural resources in an uncertain future. Walters and Holling (1990) put forth the adaptive management system as an approach to bring together managers, scientists, and the public to chart the uncertain course of future natural resource management. In light of our experiences working at the research–management interface in a highly contentious social context, we endorse the adaptive management concept.

Finally, integration and synthesis are difficult chores in ecosystem science. We submit that development of systems for sustainable management of ecosystems forms a powerful, effective form of synthesis of research results that is rich in the expression of links between concept and detail. Development and implementation of management systems can be an effective way to communicate ecosystem understanding. This medium of synthesis is comparable in value to complex simulation models and design of monitoring systems as representations of our knowledge.

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