Ecosystem Restoration and Management: Scientific Principles and Concepts

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Key questions addressed in this chapter

- Ecosystem restoration in ecosystem management
- Ecosystem restoration defined
- Naturalness and the evolutionary environment
- Examples of ecosystem restoration approaches

Keywords: Native species, fire, evolutionary environments, ponderosa pine forest, western hemlock forest, saltmarsh

"Once we restore, we are no longer retreating, tying only to slow the wave of destruction. We begin to actually advance, to regain lost ground. Can we really do it, or is the idea only hubris, human arrogance rearing its head one more time? . ..The short answer is: yes, we can really do it — to some degree. At worst we can produce something that mimics the real thing and that, given enough time, could become the real thing . . .." John P. Wiley, Jr., 1989

1 INTRODUCTION

This paper summarizes current thinking regarding ecological restoration from an ecosystem management point of view. The intended audience is natural resource professionals, natural resource interest groups, and interested members of the public. We discuss ecological restoration concepts in the context of three ecological restoration efforts with which we have been involved and which are particularly important to contemporary public land management: ponderosa pine ecosystems, forest ecosystems of the Western Hemlock Zone of the Pacific Northwest, and tidal wetlands of the Northeast. In discussing these examples we emphasize scientific principles and concepts fundamental to ecological restoration. We close our paper with a discussion of ecological restoration and human habitat needs.

Others have presented cogent syntheses of ecological restoration (MacMahon and Jordan 1994), restoration ecology (Jordan et al. 1987), and small group and community-based ecological restoration (Nilsen 1991). Although we draw upon these resources for some of our discussion, our goal is different — to discuss ecological restoration in the light of contemporary ecosystem management concepts.

Concern about the degradation of public lands and associated natural resources has been a driving force in federal land management policy since its inception (Dana and Fairfax 1980). A building consensus suggests that unless something is done to reverse the deterioration of ecosystem health, current and future generations will continue to incur increasing costs while simultaneously enjoying fewer benefits from public lands. Of particular concern is the cumulative effect of ecosystem simplification such that ecosystems are at risk of catastrophic losses of biological diversity and human habitats (Myers 1984). A cornerstone of the federal government's ecosystem management approach to solving these problems is ecosystem restoration. The Report of the Interagency Ecosystem Management Task Force (Anon 1995) stated:

> cal diversity of ecosystems and the overall quality of life through a natural resource management approach that is fully integrated with social and economic goals."

In a similar vein, the Ecological Society of America's report, *"The Scientific Basis for Ecosystem Management,"* discussed the importance of ecological restoration in the practice of ecosystem management (Christensen et al. 1995). In a previous report by the Ecological Society of America, Lubchenco et al. (1991) selected ecosystem restoration as one of twelve featured topics for priority research in an ecological research agenda in support of sustaining the biosphere. Restoration and maintenance of ecosystem health is seen as central to ecosystem management by such diverse groups as the Society of American Foresters (1993), the Southwest Forest Alliance (1996), the Sierra Club (e.g., see Berger 1997), and the American Forest and Paper Association Forest Resource Board (1993). Restoration of ecosystem health is, in fact, an international theme. The United Nations (1992) recognized ecosystem restoration as a central concern in the Rio Declaration on Environment and Development in Principle 7 which declares, "States shall cooperate in a spirit of global partnership to conserve, protect and restore the health and integrity of the Earth's ecosystems." But what is ecosystem restoration?

2 ECOSYSTEM RESTORATION DEFINED

Modern principles and concepts of ecological restoration began with the thinking of Aldo Leopold (Flader and Callicott 1991). Soon after the beginning of Leopold's professional career as a forester in the Southwestern United States, he recognized the rapid deterioration of forest and range lands because of overgrazing, intensive logging, and predator extirpation (Flader 1974). This spurred Leopold to call for viewing natural resource management as the practice of land health (now termed ecosystem health [Rapport 19951). Leopold recognized that the practice of ecosystem health required reference points — healthy, intact ecosystems still functioning as they had before disruption by intensive industrialization — and that those reference points were highly limited in the United States. Referring to the need for reference points for the practice of land health, Aldo Leopold said, "The first step is to reconstruct a sample of what we had to begin with."

Upon his re-entry into the academic community as a professor of game management, he joined forces with others at the University of Wisconsin to rebuild ap-

American settlement (Jordan et al. 1987). Using Civilian Conservation Corps, student, faculty, and community volunteers, Leopold and others began the task of ecological restoration of representative Wisconsin ecosystems at the University of Wisconsin Arboretum in 1935. That same year, Leopold began the restoration of his beloved sand county farmland just an hour's drive north of the campus. Although rehabilitation of degraded land was a widespread goal in the 1930s, the ecological restoration work of Leopold and others was different. The ecological restoration projects in Wisconsin had as their goal the restoration of native ecosystems in contrast to others where the goal was the simple revegetation of derelict lands, stopping accelerated erosion, or improving the productive potential of land.

Over the next 50 years, ecologists working on the arboretum restoration projects learned much about the structure and function of ecological systems through trial and error. In 1981 the University of Wisconsin arboretum began publishing Restoration and Management Notes as a forum for the interchange of ideas and experiences among practicing restorationists. By the 1980s, the synergy between ecological restoration (the practice) and restoration ecology (the biological science) became so apparent that it lead to the recognition of restoration ecology as a focus for developing and testing ecological theory (Jordan et al. 1987). In 1987 a professional society, the Society for Ecological Restoration, was formed; it held its first annual meeting in 1988. In 1993 the Society began publishing its scientific journal, Restoration Ecology.

2.1 Definitions

One of the first tasks of the Society for Ecological Restoration was defining ecological restoration and its principles and concepts. This task is ongoing and much discussion and debate continue among scientists and practitioners of ecological restoration (Jackson et al. 1995, Aronson and Le Floc'h 1996, Covington and Sampson 1996, Higgs 1997, Dobson et al. 1997). Nonetheless, progress has been made such that basic definitions are generally agreed upon.

The dictionary definition of "restoration" is the act of bringing back to an original or unimpaired condition. Thus, ecological restoration has as its goal the restoration of degraded ecosystems to emulate more closely, although not necessarily duplicate, conditions which prevailed before disruption of natural structures and processes, i.e., environmental conditions which have influenced native communities over recent evolutionary time (see Box 1).

Box 1
Society for Ecological Restoration Mission Statement and Summary of Environmental Policies (Society for Ecological Restoration 1993)

The mission of the Society is to promote ecological restoration as a means of sustaining the diversity of life on Earth and reestablishing an ecologically healthy relationship between nature and culture. Ecological restoration is the process of reestablishing to the extent possible the structure, function, and integrity of indigenous ecosystems and the sustaining habitats that they provide. To advance its mission, (1) SER serves as a forum for discussion and exchange of ideas; (2) SER raises awareness and promotes the expanded use of ecological restoration; (3) SER works to advance the science and art of ecological restoration, SER welcomes the participation of anyone interested in ecological restoration.

Ecological restoration involves management actions designed to accelerate recovery of degraded ecosystems by complementing or reinforcing natural processes. Ecological restoration has been viewed as ecosystem medicine where the practitioner is helping nature heal (Nilsen 1991), that is, building upon the natural recovery processes inherent in the ecosystem. Restoration ecology, the biological discipline which undergirds ecological restoration, deals with research and management experimentation to determine the mechanisms that control recovery of degraded ecosystems, and with discovering ways for safely restoring degraded ecological systems to more nearly natural conditions.

Ecosystem restoration is founded upon fundamental ecological and conservation principles and involves management actions designed to facilitate the recovery or re-establishment of native ecosystems. A central premise of ecological restoration is that restoration of natural systems to conditions consistent with their recent evolutionary environments will prevent their further degradation while simultaneously conserving their native plants and animals (Society for Ecological Restoration 1993). Practitioners of ecological restoration recognize that a failure to include human interactions with restored systems is not only unrealistic, but also undesirable for their long-term sustainability. In fact, in cases where novel conditions prevent natural system functions, ongoing management may be required to compensate for the unnatural conditions. Examples of such a circumstance are those in which restored sites are too small to support natural predator-prey dynamics or to accommodate natural disturbance regimes.

Ecological restoration is related to other practices of ecological healing such as rehabilitation, reclamation, and bioremediation, although the goals of ecosystem restoration (restoration of natural conditions) are generally more ambitious (MacMahon and Jordan 1994). Although restoration goals are often more ambitious that those of rehabilitation, this does not necessarily imply that restoration is more expensive (see discussion of restoration of Ponderosa Pine Ecosystems, below). The term "reclamation" first came into common usage after the U.S. Surface Mine Control and Reclamation Act of 1977 (Jackson et al. 1995). Reclamation refers to attempts tore-establish elements of the structure and function of ecosystems, but not complete restoration to any specified prior condition. Rehabilitation has as its goal making the land useful again, but, as in reclamation, the goal is not restoration to predisruption ecological conditions (National Academy of Science 1974). Rehabilitation might involve, for example, establishment of agricultural land on a site previously occupied by grassland. Reclamation, rehabilitation, and restoration have as their goals a continuum of outcomes from the least to the most similar to the predisturbance ecosystem (Jackson et al. 1995). Thus, all share to a greater or lesser extent some of the same techniques and can be viewed as closely allied.

In many respects ecological restoration might best be judged by whether the techniques used are setting the ecosystem on a trajectory that will eventually lead to the recovery of original ecosystem structure and function (Bradshaw 1984, MacMahon and Jordan 1994). The underlying assumption of such a view is that facilitating partial recovery of ecosystem structure and function can lead to re-establishment of natural self-regulatory mechanisms which in turn will eventually lead to restoration of the original ecosystem dynamics.

Ecological restoration, therefore, consists of a broad variety of practices designed to restore natural ecosystem structure and function. It is related to reclamation, rehabilitation, and other land recovery practices but has as its goal re-establishment of the original ecosystem structure and function. For example, in the case of southwestern ponderosa forests, ecosystem restoration might consist of removing most of the trees that postdate Euro-American settlement, raking heavy fuels from the base of the old-growth trees, prescribed burning, removing introduced noxious plants, and sowing with native herbaceous seeds. In the case of conifer forests of the Pacific Northwest and tidal wetlands of the northeastern United States, different restoration activities are required (see below).

However, ecosystem restoration should not be construed as a fixed set of procedures, nor as a simple recipe for land management. Rather, it is a broad intellectual and scientific framework for developing mutually beneficial human:wildland interactions compatible with the evolutionary history of native ecological systems. In other words, ecosystem restoration consists not only of restoring ecosystems, but also of developing human uses of wildlands which are in harmony with the natural history of these complex ecological systems.

3 WHAT IS "NATURAL"?

"Natural" is one of the most controversial concepts in ecosystem management (Christensen et al. 1995). Although it can be an ambiguous term, it is one that is ecologically, aesthetically, spiritually, and politically important as evidenced by its use in such expressions as natural area, natural range of variability, natural history, and natural processes. When used to connote the evolutionary environment, it is fundamental to conservation biology and restoration ecology. In the context of restoration ecology "natural" implies native species, structures, and processes, in contrast to exotic species, structures, and processes. Indigenous ecological components and processes are natural. Alien ecological components and processes are not. At the heart of these distinctions is the evolutionary ecology principle that species which have interacted over evolutionary time will have developed coevolved regulatory mechanisms and interdependencies that lead them to function as relatively self-regulating ecological systems.

3.1 Naturalness

Naturalness is difficult to quantify. Karr (1981) proposed an index of biological integrity for assessing the naturalness of aquatic ecosystems. His proposed index ranged from 12 in areas without fish to 60 in areas with fish composition equivalent to those in undisturbed areas. Karr's index integrates attributes such as fish species richness, indicator taxa (both tolerant and intolerant of pollution), species and trophic guild relative abundances, and the incidence of hybridization, disease and anomalies such as lesions, tumors or fin erosions. Similar approaches could be used in other ecosystems. For example, in forest ecosystems the focus might be on developing an index which integrates plant species richness, indicator animal taxa, and the incidence of hybridization, disease and anomalies in key plant and animal species.

Anderson (1991) wrestled with the problem and suggested that naturalness could be assessed by the proportion of native to non-native species, the amount of human energy needed to maintain current ecosystem conditions, and the relative change in the ecosystem if human inputs to the system cease. The concept of naturalness is sometimes best understood in the context of defining what is unnatural (Hammond and Holland 1995). In this view, a natural ecosystem would be constituted of indigenous (native) species interacting in a self-sustaining manner, i.e., species persistence by natural recruitment as opposed to managed reproduction, population dynamics regulated internally, disturbance regimes functioning within their predisruption range of variability, and trophic dynamics that are sustainable over time. An unnatural ecosystem would have a high proportion of non-native species, wide swings in population dynamics requiring management actions to prevent ecosystem simplification, and exotic disturbance regimes far outside those present before ecosystem degradation.

From a restoration ecology point of view the most important definition of "natural" is related to the concept of the evolutionary environment, a key element of defining the reference conditions for ecological restoration projects.

3.2 Evolutionary Environment

The concept of the evolutionary environment is central to conservation biology and restoration ecology. The term evolutionary environment refers to the environment in which a species or groups of species evolved — the environment of speciation (sometimes referred to as the habitat of speciation) (Mayr 1942, Smith 1958, Geist 1978).

Over evolutionary time species not only adapt to their evolutionary environment, but they may also come to depend upon those conditions for their continued survival (Mooney 1981, Wilson 1992). Thus, the greatest threat to biological diversity is the loss of evolutionary habitats (Noss 1991), and the greatest hope for reversing the losses is restoration of these habitats (MacMahon and Jordan 1994). But on what time-scale is the evolutionary environment measured?

This question has no simple answer. Evolution is an ongoing process and rates of evolution are a function of generation time, population structure, genetic variability, selection pressure, and other factors. Today's species are the product of millions of years of evolution. However, in the context of contemporary communities the relevant evolutionary environment is generally considered to be that of the past several thousand years (for most forest ecosystems this would approximate 50-100 times the average generation time of the longest lived ecological dominant trees). Based on evolutionary principles, MacArthur (1972) concluded that "...the length of time it normally takes for a species to split and diverge sufficiently to be regarded as two species is a small, uncertain number of thousands of years." A fundamental assumption is that an environmental factor can be considered as part of a species' evolutionary environment when that factor has been of sufficient intensity and duration for the factor to exert selection pressure such that the species has become adapted to it.

For North America, the recent evolutionary environment is typically taken to include Native Americans as participants in evolutionary processes over the past ten thousand years (Parsons et al. 1986, Kay 1995, Bonnicksen et al. this volume). However, the environmental pressures associated with Euro-American settlement, especially the introduction of exotic plants, animals, and land use practices, as well as the disruption of natural disturbance regimes (see White et al., this volume), are unprecedented in the recent evolutionary environment and thus viewed as disrupting evolutionary trajectories (Covington et al. 1994) and leading to pervasive degradation of ecological systems.

Ecological restoration is now seen as an approach for reversing ecosystem degradation and setting ecosystems on a trajectory more consistent with their evolutionary environment. With this approach in mind, we now present an overview of examples of ecological restoration in three major types with which we have detailed experience: ponderosa pine forests of the Southwest, conifer forests of the Western Hemlock Zone of the Pacific Northwest, and tidal wetlands of the Northeast. We use ecological restoration work in southwestern ponderosa pine to illustrate the use of detailed historical and field research based knowledge to design small-scale (l-10,000 acre) ecological restoration experiments. Conifer forests of the Pacific Northwest are used to illustrate the use of ecological restoration research in the design of a regional ecosystem management approach. Our final example, restoration of tidal wetlands in the Northeast, is used to extend our discussion of ecological restoration principles beyond forest ecosystems to aquatic and wetland ecosystems.

4 EXAMPLES OF ECOLOGICAL RESTORATION PROBLEMS

4.1 Ponderosa Pine Ecosystems of the Southwest

The Problem

The evolutionary environment of southwestern ponderosa pine ecosystems is dominated by natural disturbance regimes (e.g., fires, predation, defoliation), which have varied in kind, frequency, intensity, and extent (Covington et al. 1994). These disturbance regimes served as natural ecological checks and balances on populations and insured spatial and temporal habitat diversity (Cooper 1960, Covington and Moore 1994b). Natural fire regimes were particularly important in shaping the communities present at the time of Euro-American settlement.

Previous research has established that southwestern ponderosa pine forests were much more open before Euro-American settlement (ca. 1870) than they are today (Pearson 1950, Cooper 1960, Madany and West 1983, Covington and Sackett 1986, Covington and Moore 1994b). Before settlement, the combination of frequent (every 2-5 years), light surface fires, grass competition, and a climate unfavorable for pine establishment had maintained an open and park-like landscape, dominated by grasses, forbs, and shrubs with scattered groups of ponderosa pine trees. After Euro-American settlement, heavy livestock grazing, fire suppression, logging disturbances, and favorable climatic events favored the invasion of the open park-like vegetation by dense ponderosa pine regeneration.

Various authors (e.g., Cooper 1960, Weaver 1974, Kilgore 1981, Covington and Moore 1994a, 1994b, Kolb et al. 1994) have described symptoms of ecosystem degradation of ponderosa pine ecosystems including increases in tree density, forest floor depth, and fuel loading and consequent problems such as: (1) decreases in soil moisture and nutrient availability; (2) decreases in growth and diversity of both herbaceous and woody plants; (3) increases in mortality in the oldest age class of trees; (4) decreases in stream and spring flows; (5) accumulation of fuels; and (6) increases in fire severity and size. These symptoms are consistent with the general ecosystem health distress syndrome for terrestrial ecosystems as discussed by Rapport (1995) and Rapport and Yazvenko (1996), i.e., reductions in species diversity, leaching of nutrients, reduction in primary productivity, increased amplitude of oscillations of component species, increase in diseases, and reduction in size of dominant organisms.

Reference Conditions

Reference conditions in southwestern ponderosa pine ecosystems come from three lines of evidence: historical records, retrospective ecological analyses, and analogous sites in the Sierra Madre Occidental which

Historical Records

Reports from early travelers illustrate the changes in appearance of ponderosa pine forests since settlement. E.F. Beale who travelled through northern Arizona 1858 is quoted by C.F. Cooper (1960) as follows:

> "We came to a glorious forest of lofty pines, through which we have travelled [sic] ten miles. The country was beautifully undulating, and although we usually associate the idea of barrenness with the pine regions, it was not so in this instance; every foot being covered with the finest grass, and beautiful broad grassy vales extending in every direction. The forest was perfectly open and unencumbered with brush wood, so that the travelling [sic] was excellent."

Cooper (1960) went on to state, "The overwhelming impression one gets from the older Indians and white pioneers of the Arizona pine forest is that the entire forest was once much more open and park-like than it is today."

Before European settlement of northern Arizona in the 1860s and 1870s, periodic natural surface fires occurred in ponderosa pine forests at frequent intervals, perhaps every 212 years (Weaver 1951, Cooper 1960, Dieterich 1980, Swetnam and Baisan 1996). Several factors associated with European settlement caused a reduction in fire frequency and size. Roads and trails broke up fuel continuity. Domestic livestock grazing, especially overgrazing and trampling by cattle and sheep in the 1880s and 1890s, greatly reduced herbaceous fuels. Active fire suppression, as early as 1908 in the Flagstaff area, was a principal duty of early foresters in the Southwest. A direct result of interrupting and suppressing these naturally occurring, periodic fires has been the development of overstocked forests.

Cooper (1960) cites the writings of early expedition leaders, Whipple and Beale, both of whom travelled through northern Arizona in the 1850s. They reported that the condition of the southwestern ponderosa pine forest ". ..was open and park-like with a dense grass cover." These early descriptions of the open nature of presettlement ponderosa pine forests are in agreement with results of recent research which found that canopy coverage by trees of presettlement origin range from 17 percent to 22 percent of the surface area for unharvested sites near Flagstaff, AZ (White 1985, Covington and Sackett 1986, Covington et al. 1997).

Retrospective Ecological Analyses

Cooper (1960) stated that the structure of the southof east-central Arizona is actually that of an all-aged forest composed of even-aged groups. He noted great variation in diameter within a single age class. White (1985), in a study conducted on the Pearson Natural Area near Flagstaff, reported that successful establishment of ponderosa pine in presettlement times was infrequent (as much as four decades between regeneration events). White also determined that stems were strongly aggregated, the aggregation ranged from 3 to 44 stems within a group, with a group occupying an area that ranged from 0.05-0.7 acres. "Ages of stems within a group were also variable with the most homogeneous group having a range of 33 years and the least having a range of 268 years (White 1985)." White's findings of a pattern of uneven-aged groups near Flagstaff are in contrast to the results of Cooper (1960) for the White Mountains.

Madany and West (1983) discuss the effects that many years of heavy grazing and fire suppression have had on ponderosa pine regeneration in southern Zion National Park, Utah. They suggested that ponderosa pine seedling survival was probably greater in the early 1900s than in the presettlement days because of reduced competition of grasses (through grazing) with pine seedlings, and the reduced thinning effect that fires once had on seedlings in presettlement times.

The Restoration Process

A fundamental issue is what treatment or combination of treatments is necessary for rapidly restoring some facsimile of a healthy ponderosa pine ecosystem. The two leading management plans for ecological restoration of ponderosa pine ecosystems are prescribed burning and thinning from below (Williams et al. 1993, Covington and Moore 1994b, Arno et al. 1995, Clark and Sampson 1995).

Previous research has shown that although prescribed burning alone (without thinning or manual fuel removal) can reduce surface fuel loads, stimulate nitrogen availability, and increase herbaceous productivity, it can cause high mortality of the presettlement trees (40 percent mortality over a 20-year period) and lethal soil temperatures under presettlement tree canopies (Covington and Sackett 1984, 1990, 1992, Harrington and Sackett 1990, Sackett et al. 1996). Although some thinning of postsettlement ponderosa pine trees was accomplished by prescribed burning (Harrington and Sackett 1990), results were localized, unpredictable, and difficult to control. Furthermore, reburning, even under very conservative prescriptions (low air temperatures and low windspeed), can produce dangerous fire behavior because the continuing high density of postsettlement trees provides a continuous fuel ladder and thus a high crown fire potential. Clearly, existing research shows that prescribed burning alone (without some mechanical fuel treatments) in today's unnatural ecosystem structure will not restore natural conditions in ponderosa pine/bunchgrass ecosystems. Thus, some combination of thinning, manual fuel removal, and prescribed burning will be necessary for rapidly restoring these systems to natural conditions.

Example of Detailed Ecological Restoration Experimentation

In 1993 a small-scale ecosystem management research project was initiated at the Gus Pearson Natural Area near Flagstaff, Arizona, to test ecological restoration hypotheses (Covington et al. 1997). The research was guided by the general hypothesis that: (1) both restoration of ecosystem structure and reintroduction of fire are necessary for restoring rates of decomposition, nutrient cycling, and net primary production (NPP) to natural (presettlement) levels; and (2) that the rates of these processes will be higher in an ecosystem that is operating within some facsimile of its natural structure and disturbance regime. Specifically, the research hypothesis was that re-establishing presettlement stand structure alone (thinning postsettlement trees) will result in lower rates of decomposition, nutrient cycling, and NPP compared to thinning, forest floor fuel manipulation, and prescribed burning in combination, but that both of these treatments will result in higher rates of these processes compared to controls (see below). They further hypothesized that without periodic burning to hold them in check, pine seedling population irruptions will recur on the thin-only treatment.

Specific questions addressed were:

1. How has ecosystem structure (by biomass component) and nutrient storage changed over the past century of fire exclusion in a ponderosa pine/bunchgrass ecosystem?
2. What are the implications of these changes for NPP, decomposition, nutrient cycling, and other key ecosystem characteristics?
3. Does partial restoration (restoring tree structure alone by thinning postsettlement trees) differ from complete restoration (the same thinning, plus forest floor removal, loading with herbaceous fuels, and prescribed burning) in its effects on ecosystem structure and function?

Using a systematic approach, the authors established replicated small plot studies to test these hypotheses. Details on the experimental design, variables measured, and analytical techniques are available in Covington et al. (1997). In addition to tree density, herbaceous vegetation cover, and fuel loading, a broad range of ecological attributes related to ecosystem health are being monitored.

Dendrochronological analysis revealed that forest structure had changed substantially in the study area since fire regime disruption. Particularly striking was the population irruption of ponderosa pine from 24.3 trees per acre in 1876 to 1,254 trees per acre in 1992. The irruption of smaller diameter pine trees also created a continuous tree canopy cover at the expense of herbaceous vegetation. In 1876, only 19 percent of the surface area was under pine canopy with the balance (81 percent) representing grassy openings, whereas in 1992 pine canopy covered 93% of the area, with only 7% left as grassy openings.

Thinning resulted in the removal of a total of 5,500 bd.ft./ac (3,700 bd.ft./ac of 9-16 in dbh trees, 1,800 bd.ft./ac of 5-8.9 in dbh trees). Most of the smaller diameter trees (629 trees per acre in the 14.9 in dbh class) were utilized as latillas for adobe home construction. A major problem in utilization was what to do with the 37 tons per acre of thinning slash. Because there was no market for this material, it was hauled (70–80, 18-wheel dump truck loads) to a borrow pit and burned.

In the complete restoration treatment, approximately 21.3 tons per acre of duff were removed by raking, some of which was utilized as garden mulch. Additional treatments on the complete restoration treatment (addition of mown grass and prescribed burning) left 4.3 tons per acre. Fire intensities were low with an average flame length of six inches. Overall, soil heating was negligible except under heavy woody fuels and cambial heating was low.

During the 1995 growing season, soil moisture and temperature were consistently higher in treated areas than in the control. These microenvironmental differences between treated and control areas will likely result in higher rates of key soil processes, such as fine root production, litter decomposition, and nitrogen mineralization in treated stands, and these changes in the soil process rates will, in turn, increase herbaceous production and tree growth and resistance to insect attack. In this regard, resin flow of presettlement trees was higher on the thinned area than on the control area, as was foliar toughness, suggesting increased resistance to bark beetles and foliage feeding insects. No changes in populations of turpentine beetles was observed.

Herbaceous production responded markedly to the treatments, with the greatest response to date in the grassy substratum. By 1995, the treated areas were producing almost twice as much herbaceous vegetation as the controls.

Preliminary results from this ecosystem restoration research are encouraging. The combination of thinning and burning changed forest structure such that the restored area has shifted from fire behavior fuel model 9 (Anderson 1982), where crown fires are common, to fuel model 2, where surface fires occur but where crown fires are impossible.

The reduction in tree competition has improved on-site moisture availability and has likely increased insect resistance of presettlement trees. Grasses, forbs, and shrubs are responding favorably as well, indicating a shift away from a net primary productivity dominated by pine toward a more diverse balance across a broader variety of plants,

Ecosystem restoration research requires a long-term, interdisciplinary commitment. Ecosystem attributes being measured are likely to be in transition for the next 10–20 years before they stabilize around some long-term mean. Therefore, Covington et al. (1997) plan to continue this project for the next 24 years (eight 3-year burning intervals), with subsequent burning coinciding with the natural burning season during the spring and summer. Data on other attributes will be used to increase understanding of the restoration treatments on a range of ecosystem characteristics.

The preliminary results from the small plot studies are so encouraging that the authors have joined with the Arizona Strip District of the Bureau of Land Management to test practical ecosystem restoration treatments on an operational scale in the Mount Trumbull Resource Conservation Area, north of the Grand Canyon (Taylor 1996, Covington 1996). At Mount Trumbull, they are working with the BLM using an adaptive ecosystem management approach (Walters and Holling 1990) to restore over 3,000 acres of ponderosa pine to conditions approximating those that existed before Euro-American settlement. They are monitoring a subset of the basic ecosystem health attributes measured in the small plot study, but by virtue of the larger size of the treatment areas, they are able to measure some variables which operate on a larger-scale such as passerine bird populations, community structure of selected insect guilds (e.g., butterflies), and variables indicative of landscape-scale ecosystem health. The hope is that through such a set of integrated, adaptive ecosystem restoration projects many of the symptoms of ecosystem pathology can be alleviated while simultaneously increasing understanding of ecosystem structure and function.

4.2 Forest Ecosystems of the Pacific Northwest

The Problem

Timber harvesting has been an important element of the economy of the coastal Pacific Northwest since the arrival of European settlers in the 1800s. Although the extensive forests were initially considered to be obstacles to be cleared to make way for agriculture, their economic value as sources of wood was soon recognized. In the late 1800s and early 1900s, rates of harvest began to increase, and escalated greatly following World War II. By the late 1980s, most forests on private lands had been harvested at least once, and old-growth forests were generally limited to federal lands. More than 80 percent of pre-logging old-growth forests in the region had been removed (Booth 1991).

During the 1970s and 1980s, management of federal forests became increasingly controversial. Much of the concern focused on the habitat requirements of the northern spotted owl (*Strix occidentalis caurina*), a resident of old-growth forests. Largely because of continued loss of suitable habitat and the lack of regulations or policies to protect northern spotted owls, in 1990 the U.S. Fish and Wildlife Service listed the subspecies as threatened under the Endangered Species Act of 1973. Listing of the northern spotted owl greatly reduced the quantity of timber sold from federal lands in western Oregon and Washington, and northern California.

Although preservation of the spotted owl has been a focal point of the debate, the owl also served as a surrogate for other organisms of old-growth forests, and of the forest itself. The real questions were much broader, and included the following: What are appropriate management objectives for federal forests?, How much old-growth forest should be retained?, Is clearcut logging an acceptable harvest method?

In an attempt to resolve the complex issue, on April 2, 1993, President Clinton convened a forest conference in Portland, Oregon, at which he instructed federal agencies to work together and develop a "scientifically sound, ecologically credible and legally responsible" plan to restore, protect, and maintain the long-term health of forests, wildlife, and waterways. This plan would also provide for human and economic concerns and "produce a predictable and sustainable level of timber sales and nontimber resources that will not degrade or destroy the environment."

Following the conference, an interdisciplinary group of scientists was brought together as the Forest Ecosystem Management Assessment Team (FEMAT), to "identify management alternatives that attain the greatest economic and social contribution from the forests of the region and meet the requirements of the applicable laws and regulations..." (USDA et al. 1993). Subsequently the President chose an alternative ("Option 9") which would include approximately 7.4 million acres within Late-Successional Reserves, 2.6 million acres within Riparian Reserves, and 1.5 million acres of Adaptive Management Areas within which application and testing of ecosystem management techniques are encouraged. New, more restrictive, standards and guidelines were also developed for timber harvest within the approximately 4 million acres of federal lands outside of reserves and other areas withdrawn from timber harvest. Following the preparation of a Final Supplemental Environmental Impact Statement (USDA/USDI 1994a), on April 13, 1994, the Secretaries of Agriculture and Interior signed a joint Record of Decision (USDA/USDI 1994b) to implement this plan.

The Record of Decision applies to federal forests within the range of the northern spotted owl. However, in this example we focus on the Western Hemlock Zone, the most extensive vegetation zone in western Oregon and Washington, and the most important in terms of timber production (Franklin and Dyrness 1973). This zone is dominated by western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), Douglas-fir (*Pseudotsuga menziesii*), and grand fir (*Abies grandis*).

The Forest Ecosystem Management Assessment Team was specifically asked to develop alternatives for long-term management which met the following objectives (USDA et al. 1993):

- Maintenance and/or restoration of habitat conditions for the northern spotted owl and the marbled murrelet (*Brachyrampus marmoratus*) that will provide for viable populations, well distributed within their current ranges on federal lands.
- Maintenance and/or restoration of habitat conditions to support viable populations, well distributed across their current range, of species known (or reasonably expected) to be associated with old-growth forest.
- Maintenance and/or restoration of spawning and rearing habitat on federal lands to support recovery and maintenance of viable populations of anadromous fish species and stocks and other fish species and stocks considered "sensitive" or "at risk."
- Maintenance and/or creation of a connected or interactive old-growth forest ecosystem on federal lands.

Accomplishing these objectives will require an unprecedented application of principles of ecological restoration across 24.3 million acres of federal lands (USDA et. al 1993), at stand-level, watershed, and regional scales.

Reference Conditions

Pollen records from the Pacific Northwest suggest that forests of modern composition were first established about 6,000 years BP following retreat of lowland glaciers (Brubaker 1991). These forests consist of long-lived conifer species which become massive as they age. With time, these forests develop characteristic Pacific Northwest old-growth attributes: patchy, multi-layered canopies with trees of several age classes, large live trees, and an abundance of snags and fallen logs. Although rate of development for these structural characteristics is variable, old-growth characteristics commonly begin to appear in unmanaged forests at 175-250 years of age (USDA et al. 1993).

These forests provide habitat for an exceedingly rich bird and mammal fauna (Harris 1984), with some species occupying unique ecological niches. One such species, the red tree vole (*Aborimus longicaudus*), is the most specialized vole in the world and the most arboreal mammal in North America (Maser et al. 1981). Northern flying squirrels (*Glaucomys sabrinus*) are the only North American forest mammal that consumes lichens as their primary forage (Harris 1984). Both of these mammals are important prey species for the northern spotted owl, which is closely associated with old-growth forests. Arthropods are also very diverse, with as many as 7,000 species inhabiting these forests (USDA et al. 1993). Although forests of the Pacific Northwest are relatively young, as measured on geological time scales, a rich fauna has co-evolved with these plant communities.

Natural fire-return intervals for these forests are variable, ranging from less than 100 to several hundred years (Agee 1991). Intense fires are important elements of the natural fire regime, but lower severity fires also occur (Agee 1991). Unlike southwestern ponderosa pine forests, fire suppression has only minimally influenced forests of the region. Fire suppression became effective after 1910, and with long fire-return intervals, the effects of 85 years of fire exclusion have been relatively minor (Agee and Edmonds 1992).

The forest was not an unbroken block of old-growth. Prior to European settlement, the regional landscape consisted of a shifting mosaic of forest communities in varying stages of successional development following disturbance. During the early 1800s, prior to extensive fires caused by settlers during the 1840s, nearly 40 percent of forests in the Coast Range of

These younger forests, however, were structurally different than those regenerated after timber harvest. The following discussion focuses on management of young stands to accelerate the development of structural attributes of old-growth forests, and provides an example of restoration challenges faced by forest managers in the Pacific Northwest.

Restoration Goals and Treatments

The heart of the plan is a 10 million-acre federal system (USDA and USDI 1994a) of late-successional and riparian reserves. These reserves were established to provide an inter-connecting network of late-successional and old-growth forests, but at the present time they contain large areas of younger forest. More than 50 percent of the area within late-successional and riparian reserves supports younger forests (USDA and USDI 1994a). Most of these younger stands were usually established following fire or timber harvest. Regeneration of these stands was designed to produce high yields of lumber, not to produce old-growth forest characteristics.

With enough time, some of these forests and associated processes, communities and species will assume old-growth characteristics without intervention. Others may not, or will only do so over greatly lengthened time frames.

Acceleration of the development of old-growth characteristics in these stands is desirable, and would likely improve the long-term potential for success of the Northwest Forest Plan. Northern spotted owls and marbled murrelets may be important beneficiaries of such management. For both of these species, there is concern about population viability during a transition period lasting until habitat conditions improve significantly (USDA et al. 1993).

Most young forests within the reserve system have been managed under an even-aged system. Following clearcutting, regeneration was accomplished with site preparation, planting of nursery-grown seedlings, and control of competing vegetation. Standing snags were commonly removed because of safety concerns. Often these forests were thinned 10-20 years after establishment to control density and ensure uniform spacing. Many such stands subsequently go through a stem exclusion or self-thinning stage during which much of the understory is lost (Oliver and Larson 1990).

The primary objective of these practices is to create a uniform conifer stand which quickly achieves crown closure and dominates nonconifers (Tappeiner et al. 1992). This process of stand development is, however, quite different from that following natural disturbance.

continue for 40-100 years (Agee 1991), rather than as a pulse of regeneration extending for a relatively brief period. Many old-growth trees were apparently established in relatively open conditions with little competition for 100 years or more (Franklin et al. 1981). Such stands may not have gone through the self-thinning stage associated with commercial forests. Understories persisted, and younger trees were established and became intermediate canopies. The dominant old trees retained deeper crowns, thus providing nest sites and thermal cover for wildlife species such as spotted owls and marbled murrelets.

The Northwest Forest Plan encourages the use of silviculture to "accelerate the development of young stands into multilayered stands with large trees and diverse plant species, and structures that may, in turn, maintain or enhance species diversity." Treatment will focus on stands that have been regenerated after tree harvest or on stands that have been thinned and will include, but not be limited to: (1) thinning or managing the overstory to produce large trees, release advanced regeneration of conifers, hardwoods, or other plants, or to reduce risk from fire, insects, disease, or other environmental variables; (2) underplanting and limited understory vegetation control to begin development of multistory stands; (3) killing trees to make snags and logs on the forest floor; (4) reforestation; and (5) use of prescribed fire (USDA et al. 1993, USDA and USDI 1994).

Tappeiner et al. (1992) discussed systems which can be used to accelerate the development of stand structures which are important for northern spotted owls, and to grow habitat in stands where it is unlikely to develop naturally. Simulated outcomes of several silvicultural prescriptions, based on data from actual stands, were included. The following is an example of a prescription and simulated response for a Douglas-fir forest in the Coast Range of Oregon.

The stand contained Douglas-fir, grand fir, and big leaf maple, with an initial density of 881 stems/acre. At age 40 years, 50 percent of the conifers with diameters from 10 to 16 inches were removed and one-hundred conifers/acre were planted. At age 60 years, 50 percent of trees with diameters from 10 to 22 inches were converted to snags, logs on the forest floor, or removed, and 100 conifers/acre were planted. At age 80 years, 60 percent of the conifers 8 to 22 inches in diameter were made into snags, down logs, or removed, with 224 conifers and 70 hardwoods remaining. At age 120 years, the stand was projected to have a multi-story canopy with 53 percent cover, and several trees/acre greater than 42 inches in diameter. Untreated, the stand would had a single layered canopy, no trees with diameters greater than 42 inches, and a sparse understory. Diameter distributions of the treated stand were similar to those measured in stands providing suitable habitat for northern spotted owls (Tappeiner et al. 1992).

Although this example was developed for a Douglas-fir forest in the Coast Range of Oregon, similar approaches could be applied in other areas, including the mixed conifer forests of southern Oregon and northern California. Tappeiner et al. (1992) provide the following suggestions for silvicultural systems designed to emulate natural disturbance and stand development:

- Favor some large trees with numerous limbs for potential nest sites.
- Use hardwoods to help develop a multi-layered stand.
- Encourage the growth of advanced regeneration of shade-tolerant conifer and hardwood species.
- Establish new regeneration by planting or seeding in young stands after making small openings or reducing overstory density in parts of a stand.
- Vary the distribution of overstory trees when thinning. Make openings for new regeneration and to release advanced regeneration.
- When thinning, leave some trees in the smaller crown size classes to help promote a layered stand.
- In stands with irregularly spaced trees, consider a crown thinning to release individual trees while maintaining the irregular spacing.

Although the primary goal of silviculture systems for late-successional reserves is the restoration of old-growth characteristics, important economic benefits can be derived from thinning these stands. Education programs may be required, however, to illustrate the ecological benefits of such activities. Importantly, managers must establish and maintain a high level of public trust when planning silviculture systems for reserves.

Adaptive Management and Ecosystem Restoration

Ecosystems are extremely complex, and often it is difficult or impossible to predict accurately the impact of management actions on future conditions. Failure to act also has unforeseen consequences. The Northwest Forest Plan resolves this dilemma by requiring adaptive management (Holling 1978, Walters 1986).

Adaptive management as envisioned in the forest plan is "a continuing process of action-based planning, monitoring, researching, evaluating and adjusting with the objective of improving the implementation and achieving the goals" of management standards and guidelines. Simply stated, managers and scientists learn from experience and use this knowledge to improve subsequent actions.

Silvicultural activities in late-successional reserves provide a good example of the application of adaptive management. Initially, existing knowledge of silviculture is reviewed and synthesized as a basis for development of a prescription. During and after implementation, a scientifically and statistically credible monitoring and evaluation program determines whether development of old-growth characteristics has been achieved, and, finally, new knowledge and information is incorporated into new prescriptions for similar areas.

Because forest succession occurs slowly from a human perspective, long-term monitoring programs are required. Successional data from these programs will provide important information upon which to refine simulation models of stand development, and more accurately project the outcomes of silviculture systems.

Restoration Challenges

Restoration of old-growth forests and processes will be difficult and exceedingly complex. We have focused on the use of silviculture to restore old-growth characteristics at the stand level. We have not addressed important issues such as landscape level integration, restoration of fire as a natural process, or restoration of anadromous fish habitat. Stand-level restoration will provide key building blocks with which to restore and maintain landscape and regional scale ecosystems. The ultimate ecological test of the Northwest Forest Plan will be its ability to provide an evolutionary environment which maintains native species and natural processes and allows them to continue to evolve.

4.3 Salt Marsh Ecosystems of the Northeast

The Problem

Over the last half century the salt marshes along the Northeast coastline have been severely impacted because of human activities (Anon 1961, Tiner 1984). They have been dredged, filled, and impounded, which has either destroyed the marsh vegetation or modified it floristically. In Connecticut, 40 percent of the original salt marshes that fringed Long Island Sound have been destroyed. Thus, the need for restoration is obvious not only to compensate for these losses but also to restore degraded systems. Because of tidal restriction along the valley marshes which characterize many of the New England type salt marshes, vast acreages of *Spartina*-dominated communities have been transformed into monocultures of *Phragmites australis* (common reed) (Haslam 1973, Niering and Warren 1980). Those filled but not developed also exhibit a similar monoculture. There is an urgent need to restore tidal flushing to restricted systems, reclaim filled marshes and encourage *Spartina* plantings in those areas where marshes can be recreated and thus reconnect these productive tidal wetlands with the surrounding estuarine waters.

The Reference Marsh

The reference salt marsh is an undisturbed estuarine, emergent wetland dominated by *Spartina alterniflora* (saltwater cord grass) and *Spartina patens* (salt meadow cordgrass) (Miller and Egler 1950, Niering and Warren 1980, Nixon 1982, Teal 1986, Bertness 1992). The former, growing l-2 meters in height, characterizes the low marsh and it is flooded by every tidal cycle. It is replaced landward by the high marsh S. *patens* which is flooded periodically by spring high tides. A third belt of *Juncus gerardii* (black grass) forms a border near the upland and is replaced by an upper-most border of *Panicum virgatum* (switch grass) and/or *Iva frutescens* (marsh elder). Where the disturbance occurs along the marsh/upland interface *Phragmites* may form the typical upper border vegetation. This marsh system is flushed by estuarine waters with salinity ranging from 2030 ppt. It exhibits also a distinctive set of animal populations some of which are restricted to the low marsh whereas others are more typical of the high marsh (Olmstead and Fell 1974).

Goals of Restoration

The major goal is to restore salt marsh systems lost historically and recreate the ecological link between the tidal marsh and contiguous estuary so that the high productivity of the tidal marsh-estuarine system can be restored. These systems carry on a diversity of functional roles or values in terms of finfish and shellfish productivity and shoreline stabilization (Niering 1985, Mitsch and Gosselink 1993).

The Restoration Process

A diversity of restoration strategies can be employed depending upon the nature of site degradation. In the case of tidal restriction, the aim is to restore tidal flushing and attempt to recreate a salinity regime similar to that which previously existed (Rozsa and Orson 1993). With salinities above 20 ppt, *Phragmites* will be killed or sufficiently suppressed to favor the re-entry of the *Spartina* grasses (Capotosto and Spencer 1988, Tiner

1995). In other sites the restoration process may involve removal of spoil or dredged material from a filled salt marsh which may now be *Phragmites*-dominated. Here spoil is removed to expose the original salt marsh peat surface (Capotosto 1993, Waters 1995) and then the creek channels are recreated to restore tidal flushing. Marsh elevations are critical in terms of tidal flooding to favor the establishment of *Spartina alterniflora*. A gentle slope that falls within the range of mean high and mean low tide is required. This is also the prerequisite for any planting of S. *alterniflora* where shoreline stabilization is desired or where new marsh is being created. High-marsh *Spurtinu patens* can be recreated at slightly higher elevations either under natural conditions or by planting, but high marsh is not as easy to recreate as low marsh because it is controlled by a complex of environmental factors. Another parameter in the restoration process is to avoid flooding of private property during major storms. The use and availability of self-regulating tidal gates invented by Thomas Steinke, Director of the Fairfield Conservation Commission, has greatly aided the marsh restoration process in highly developed areas (Steinke 1986, 1995a,b).

Case Histories

Several case histories will be briefly described to illustrate the feasibility of salt marsh restoration in various ecological settings (Rosza and Orson 1993). Such efforts also serve as invaluable models where one can actually observe firsthand results of ecological restoration.

The Hammock River (Connecticut) valley marsh on Long Island Sound represents a 250-acre system in which the upper reaches were restricted by tidal gates early in the century, transforming the typical *Spurtinu*-dominated wetland to a monoculture of Phragmites. To reverse this trend, one of the four tide gates was opened in the summer of 1985. Now more than a decade later *Phrugmites* has been dramatically suppressed and the area is now dominated by *Spurtinu* and other salt marsh vegetation.

Another successful marsh restoration project is at the Barn Island Wildlife Management Area (Connecticut) on the Connecticut/Rhode Island border. Here a valley salt marsh was severely restricted in the late 1940s with only an 0.5-m opening connecting the adjacent estuary (Miller and Egler 1950). The salt marsh was transformed from a Spartinu-dominated vegetation to a *Typha angustiflolia* (narrow-leaved cattail) marsh with areas of *Phrugmites* restricted to the marsh borders. In 1978 a five-foot culvert was installed, followed by another seven foot shortly thereafter in order to increase tidal flushing. Salinity of the adjacent estuary was restored (28-33 ppt) to the impounded area. By the mid 1980s most of the cattail was dead and *Spurtinu* grasses dominated the area (Sinicrope et al. 1990, Barrett and Niering 1993). With the restoration of the plant community, typical salt marsh animal populations have also become established (Fell et al. 1991). After more than a decade, functional equivalence is being restored, not unlike the productivity and trophic structure in the nearby reference system.

Marsh restoration by planting has also been documented in the Northeast but especially in Southeast (North Carolina) where extensive salt marsh areas have been created on dredged material (Broome et al. 1986, Broome et al. 1988, Broome 1990). In the Northeast, this has been done on a less extensive scale within the intertidal low marsh zone especially to favor shoreline stabilization (Garbisch and Garbisch 1994). Recreating the elevation typical of the low marsh so that the site is flooded by every tidal cycle is, as previously mentioned, the major prerequisite. Planting *S. alterniflora* 20 in apart and protecting it from grazers such as geese until well established is critical. S. *alterniflora* plantings following an oil spill have resulted in successful restoration (Bergen et al. 1995).

Attaining Functional Equivalence and Monitoring and Establishment of a Buffer Zone

The ultimate goal of salt marsh restoration is to create a self perpetuating ecosystem with its productivity, biogeochemical cycling, and food chain support comparable to the reference or control marsh system. Much literature now exists on this subject from the Southeast, where marsh restoration and creation have been underway since the 1970s (Craft et al. 1988, Sacco et al. 1994, Thompson et al. 1995). Literature is also available from the Northeast (Fell et al. 1991, Allen et al. 1994, Peck et al. 1994, Spelke et al. 1995). It has been shown that various aspects of functional equivalence can be attained within a decade or less depending upon the region. For some functions several decades may be required. Thus, monitoring a minimum of five years upon the completion of the project is basic. This allows time for management correction and assessing the development of functional equivalence.

A further requirement is the establishment of a buffer zone along the upland to accommodate continued sea level rise. Two studies in the Northeast have documented the potential effects of sea-level rise on the marsh vegetation toward a more hydric/less productive phase (Warren and Niering 1993, Nydick et al. 1995). The current rate of sea level rise is one inch per year and this rate is predicted to increase in the future with climate warming (Warrick 1993). Therefore, an undeveloped buffer of 50-100 ft or more is needed to provide for the landward movement of the marsh with sea level rise and overall protection of the restored system.

Finally, it should be noted that the potential for restoration should not substitute for permitting salt marsh destruction because of development. All possible and prudent alternatives should be explored prior to sacrificing a self-perpetuating functional tidal salt marsh ecosystem (Oviatt et al. 1977, Kusler and Kentula 1989, Moy and Levin 1991).

5 A SYSTEMATIC APPROACH TO ECOLOGICAL RESTORATION

Far too many ecological restoration projects have been started without clear definition of restoration goals and with little attempt to evaluate the success quantitatively. Bradshaw (1993) argued strongly that ecological restoration should follow a scientific approach: (1) be aware of other relevant work, (2) carry out experiments to test ideas, (3) monitor key indicator parameters, (4) design further experiments and tests based on results of monitoring, and (5) publish peer reviewed results and conclusions. Kaufmann et al. (1994) discussed the importance of a systematic approach in ecosystem management including the determination of reference conditions, determination of current conditions, and using coarse- and fine-filter analyses to determine if goals are met. Oliver et al. (1994) suggested an eight-step systematic approach for achieving forest health which is relevant to ecological restoration. Walters (1987) emphasized the importance of clearly stating assumptions about ecosystem behavior, the building of explicit models that synthesize this knowledge, and testing this knowledge in adaptive learning experiments.

Based on these ideas and other sources, we have developed a stepwise systems analytic approach to the design of ecosystem restoration experiments (Table 1). Most steps are straightforward and broadly discussed in the adaptive ecosystem management literature. Of these steps, step 3, determining reference conditions is most explicit to ecological restoration.

Adaptive ecosystem restoration and management involves a broad variety of practices for designing and testing ecological restoration treatments. A systematic ecological techniques, retrospective ecological analysis, and dendrochronology, along with other techniques (see Kaufmann et al. 1994, Morgan et al. 1994), are used to determine the natural structure and function of the ecological system to be restored. Goals and performance measures must be defined in measurable terms. Assumptions about ecosystem dysfunction must be stated. A specific set of scientifically-based alternative treatments for restoring ecosystems to the desired condition must be developed. Finally, monitoring and evaluation procedures are used to determine where the restoration worked and where it did not. A central assessment is whether the ecosystem being restored has been set on a trajectory such that structural and functional equivalency to the reference system will be attained. This information is then fed back into the body of scientific and managerial knowledge for future ecosystem management decisions.

Table 1. A systems analytic approach to adaptive ecosystem restoration.

1. Clearly diagnose the symptoms and causes of the ecosystem health problem. What are the symptoms that suggest the ecological system has been degraded and what are the underlying mechanisms (Rapport 1995, Covington et al. 1994)?
2. Determine reference conditions. What was the condition of the ecosystem before degradation (Kaufmann et al. 1994, Morgan et al. 1994)?
3. Set measurable ecological restoration goals (National Research Council 1992). How close to reference conditions do you intend to get? How will you know if you are moving in the right direction?
4. What factors are most limiting to the restoration process?
5. Develop alternative ecosystem restoration hypotheses (Walters and Holling 1990).
6. Design restoration treatments that will allow you to test the alternative hypotheses (Bradshaw 1993).
7. Monitor ecosystem conditions and evaluate hypotheses.
8. Feed the results back into the design and implementation of ecological restoration treatments — adapting management based on results and changing goals (Kaufmann et al. 1994).

6 ECOSYSTEM RESTORATION AND HUMAN HABITAT NEEDS

Philosophically, ecosystem restoration is founded on symbiosis with land, economic, public, and private;" as "a protest against destructive land use;" as an effort "to preserve both utility and beauty;" as "a state of harmony between men and land;" and finally, as "a positive exercise of both skill and insight, not merely a negative exercise of abstinence and caution."

Given the wide variety of human needs and goals for federal lands and waters, it seems unlikely that vast areas will be restored to completely natural conditions. In fact, keeping some areas in a somewhat artificial state may be desirable so long as such action does not impair their long-term sustainability. Areas dedicated to wood fiber production, livestock grazing, intensive recreation, and many other human habitat uses might fall into this category.

Setting degraded ecosystems on the path to recovery of natural structure and function seems broadly warranted. Ecological restoration, even though partial, can go a long way toward reducing the undesirable symptoms of dysfunctional ecosystems and benefit not only future generations but also those involved in the restoration process. In fact, some have suggested that the transformation of those involved in ecological restoration is one of the major benefits to be gained from such projects (Dodge 1991, Jordan 1993).

7 CONCLUSIONS

Ecological restoration has as its goal the restoration of degraded ecosystems to resemble, or emulate more closely conditions that prevailed before disruption of natural structures and processes. A key concept in restoration ecology is that of the reference conditions defined as the range of ecosystem conditions (including structure and function) which have prevailed over recent evolutionary time. Underlying the idea of reference conditions is the concept of the evolutionary environment -the environment in which species have evolved. Ecological restoration consists of management actions designed to accelerate recovery by complementing or reinforcing natural processes.

Key ecological restoration concepts and principles have been discussed using examples from ponderosa pine ecosystems of the Southwest, forest ecosystems of the Pacific Northwest, and salt marsh ecosystems of the Northeast. A wide variety of methods can be used to determine reference conditions, ranging from historical documentation to paleoecological reconstructions and to locating contemporary ecosystems which can serve as analogs for what the degraded ecosystem might have been like had it not been disturbed.

Once reference conditions have been determined, then sets of management actions must be identified that can accelerate recovery of the ecosystem. Close attention must be given to restoration of both structure and processes, including natural disturbance regimes, if restoration is to be successful. These management actions can be viewed as working hypotheses to be tested in closely monitored management experiments.

For ecological restoration to serve as a viable approach to implementation of ecosystem management, it must not be viewed as a rigid set of procedures nor as a simple recipe. Rather, it must be viewed as a broad intellectual framework for meeting ecological habitat needs for all organisms, including those of humans, by managing in harmony with the natural ecosystem processes and components characteristic of the recent evolutionary environment of the biota.

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