Annu. Rev. Energy Environ. 1996. 21:167–89

RESTORATION ECOLOGY: The State of an Emerging Field

John Cairns, Jr. and John R. Heckman

Department of Biology, Virginia Polytechnic Institute and State University,
Blacksburg, Virginia 24061

KEY WORDS: ecological restoration, ecosystem services, biocultural restoration, ecosystem repair and healing

ABSTRACT

The field of restoration ecology represents an emerging synthesis of ecological theory and concern about human impact on the natural world. Restoration ecology can be viewed as the study of how to repair anthropogenic damage to the integrity of ecological systems. However, attempts to repair ecological damage should not diminish protection of existing healthy ecosystems. Restoration ecology allows for the testing of ecological theories; however, restoration ecology is not limited to, nor is it a subdiscipline of, the field of ecology. Restoration ecology requires approaches that integrate ecology and environmental sciences, economics, sociology, and politics. This review illustrates these points by providing a conceptual map of the origin, present practices, and future directions of the field.

CONTENTS

1056-3466/96/1022-0167$08.00

INTRODUCTION

Throughout human history, societies have realized to some degree that they depend on the natural world (1). However, only recently have population pressures forced society to inspect and catalog the damages incurred by its use of natural systems. As the impact of the damage has become clear, society has developed several technologies and fields of study aimed at relieving or reducing these disturbances. Modern forestry, waste treatment technologies, mining reclamation, and ecotoxicology are examples of endeavors that focus on either enhancing specific aspects of nature or removing human impingements on the natural world. However, these fields do not incorporate the study of methods and processes involved in restoring the ecological structure and function that supplied these services initially. Such study is the purpose of the field of restoration ecology, which has only been significantly developed over the past decade and has only been acknowledged as a fully independent discipline within the past few years.

Among practitioners, debate continues as to whether restoration ecology is a subunit of ecology or an entirely new discipline. Although many theories in the field stem directly from community and ecosystem ecology, the focus on the human factor extends the field beyond a strictly ecological framework. The field does not fit the classical model of a scientific discipline because its bounds are not as well defined as those of geology, chemistry, or physics.

Restoration ecology is quite simply the study of ecological restoration. A distinction is often made between ecological restoration and restoration ecology because the former is an action, whereas the latter is a science with underlying theories and a research agenda. Restoration ecology is a bridge between the social and natural sciences. The field includes the study of all applications of ecological theories designed to relieve acute anthropogenic disturbances and restore self-maintaining ecological systems. Thus, restoration ecologists are faced with the difficult task of integrating many ongoing environmental sciences into a coherent process for restoring and maintaining the functioning natural world.

Because of the enormous breadth of this emerging field, our aim in this review is not to provide an exhaustive list of all literature pertinent to restoration ecology. Instead, we frame the reasons and rationale behind the development of the discipline, comment on the scientific and social aspects of restoration ecology, and provide illustrative examples of research. With this approach, we hope to make clear the extent and importance of restoration ecology within the limited space of a single review.

DEFINING RESTORATION

In a field that encompasses as many disciplines as restoration ecology, an unequivocal definition of goals and directions is necessary. As stated above, restoration ecology can be defined as the study of ecological restoration. However, much of the restoration literature to date is filled with debate on the very meaning of ecological restoration. From this discussion, two main emphases have arisen: 1. goal-oriented restoration focusing on the science of reconstructing functioning ecological systems, 2. process-oriented restoration dealing with the integration of ecological principles and human social systems (Table 1). Rather than splitting the field, this dichotomy clarifies the scientific and social nature of restoration ecology and further emphasizes that both factors must be considered equally.

The National Research Council (NRC), in its volume *Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy* (2, p. 18), provides a goal-oriented definition of restoration: “the return of an ecosystem to a close approximation of its condition prior to disturbance.” Although this definition is attractively simple at first, it presents two questions that are at the core of restoration ecology. First, what frame of reference should be used to establish the predisturbance condition? A true predisturbance condition can almost never be found because of poor detailed ecological records; some approximation must be chosen, which is often difficult in areas of extreme disturbance (e.g. urbanized landscapes). Second, what comparisons should be made between recovering and reference areas? As discussed in the section on frames of reference, the choice of which ecosystem characteristics to compare can drastically change the outcome of the comparison.

A paramount value of a goal-oriented definition of restoration is its emphasis on restoring a self-maintaining and/or self-perpetuating ecosystem (i.e. restoring dynamic changes characteristic of all mature ecosystems which, over long periods of time, have ecologically acceptable structure and function despite species turnover). Another emphasis of goal-oriented restoration is on integrating a restored patch into the larger ecological landscape. Even the challenge of defining such phrases as “acceptable structure and function” and “integration into the surrounding landscape” adds to the task of restoration ecologists. However, only by defining, addressing, and meeting such stringent goals will restoration ecologists be able to repair ecological damage satisfactorily.

Table 1 Definitions of ecological restoration useful on different scales

Emphasis	Example definition	Useful focus
Goal-oriented	The return of an ecosystem to a close approximation of its condition prior to disturbance (Reference 2)	Addresses the problem of finding references for restored areas
		Emphasizes the choice of parameters for ecological comparisons
		Identifies problems in facilitation of succession
Process-oriented	The process of repairing damage caused by humans to the diversity and dynamics of indigenous ecosystems (Reference 3)	Includes social forces responsible for ecological damage in restoration plans
		Emphasizes the role of community action in restoration
		Recognizes the limits of restoration in light of further disturbance and social situation

The goal-oriented NRC definition provides a starting point for objective research into the design of ecological restoration. However, this definition does not specify many of the causes underlying the need for restoration. A process-oriented definition of restoration shifts the emphasis from replicating a predisturbance condition to taking the actions necessary to ensure the return of a natural ecological state. Jackson et al (3) define restoration as “the process of repairing damage caused by humans to the diversity and dynamics of indigenous ecosystems.” Their definition of restoration includes four subsections: a judgment of need for restoration, an ecological approach to restoration, the necessity of goal setting and evaluation, and an appreciation for the limits of restoration. These concepts help elucidate the real-world framework within which these goal-oriented tenets of system reconstruction and judgments of ecological integrity must be applied. Social implications such as legislative and economic contingencies, community opinion, and risk evaluation must be understood to ensure success in any restoration project. Social realities are often as important to restoration plans as scientific theories and predictions.

RESTORATION OF ECOSYSTEM SERVICES: THE VALUE OF A GOAL-ORIENTED PERSPECTIVE

Outcomes of resource exploitation and conservation practices are uncertain (4). Therefore, models for sustainable use and related strategies must be viewed cautiously. If the present global rate of human population growth increases and natural resource exploitation, habitat destruction, and loss of biodiversity continue beyond the year 2000, the probability is high that major initiatives will have to be undertaken to achieve anything close to sustainable use as it is presently understood.

A useful method for interpreting changes in the environmental support system is to quantify ecosystem services. Ecosystem services may be defined as any ecological functions perceived as beneficial to human society (Table 2). The integration of social and ecological values into economically important units makes it easier to compare inherent ecological value with economic resource use. If the goal of restoring or enhancing delivery of ecosystem services is part of an ecological restoration strategy and the public understands that these services are part of the ecological life support system upon which human society depends, society may be more supportive of large-scale ecological restoration.

For most of the time humans have existed, our life support system has been entirely ecological. Human society now relies on both technological

Table 2 Illustrative ecosystem services and their underlying ecological functions

Ecosystem service	Related ecosystem function	References
Biomass production for food, building materials, and fuel	Capture of solar energy through photosynthesis, regeneration of essential nutrients and soils	8, 83–87
Assimilation of pollutants	Decomposition, detritus processing	5, 87, 88
Flood control, water purification, water transportation	Maintenance of the hydrological cycle	9, 86, 89, 90
“Pest” species control	Predator/prey relationships with insectivorous birds, insects bats, etc	5, 83
Provision of new compounds for medicinal and other uses	High biodiversity through competition, selection, and speciation	5, 73, 86, 91, 92
Maintenance of a breathable and protective atmosphere	Biogeochemical interactions	8, 83, 86
Aesthetic and spiritual values	All natural functions	8, 93, 94

and ecosystem services (5). Following the agricultural revolution and, perhaps more significantly, the industrial revolution, human population size increased enormously, as did expected levels of affluence. Furthermore, the shift in human population distribution was toward large urban areas where technological services delivered food, power, shelter, and other amenities. The power of technologies such as waste treatment and mechanized agriculture to provide basic services for affluent societies quickly caused major changes in society's relationship with nature (1). However, opportunities for individuals in these settings to observe natural systems and to reflect upon their dependence on these systems diminished dramatically.

If one accepts the hypothesis that human society's life support system requires both technological and ecosystem components, then it is difficult to visualize sustainable use of the planet at the projected population densities and expectations of affluence without robust delivery of both types of services. An illustrative example is the eco-attraction/human terrarium known as BioSphere 2. Avise (6) cites an estimated cost of $9 million per inhabitant for the artificial provision of all the ecosystem services that earth provides for free. Furthermore, with both population and expectations of affluence increasing on a finite planet, ecological restoration coupled with a focus on ecosystem health seems to be the only viable option for ensuring delivery of per capita ecosystem services at their present levels (7, 8).

An excellent example of measuring ecosystem services is given by Van Wilgen et al (9) in their discussion of South African fynbos ecosystems. Shrubland vegetation characteristic of fynbos areas ensures high quality water supplies because of its low water use, high erosion control, and adaptation to fire. Invasion of the systems by alien tree species can drastically alter the hydrological dynamics, resulting in reduction of streamflows. Using an economic modeling analysis, Van Wilgen et al (9) show that the cost of water produced by fynbos ecosystems, including the cost of managing for alien plant exclusion, is 14% less than water costs without management of invading species. Even if we ignore the many associated services that would also be provided with fynbos restoration, such as wildlife habitat provision and cultural preservation, this analysis presents a convincing reason for preserving the fynbos system for economic reasons alone.

Using the need for ecosystem services as the primary justification for ecological restoration presents problems. Biotic impoverishment, or loss of species richness, is well documented (10). However, what the relationship is between species richness or diversity and the delivery of ecosystem services is not clear, and it is not likely to become clear in the very near future. Because ecological restoration has focused on re-establishment of species far more than on re-establishment of ecological function, how such restoration will improve the delivery of those functions (i.e. services) that were once provided by the undamaged or relatively undamaged ecosystem is not clear. The extent to which managed systems (e.g. agribusiness) can deliver services that are qualitatively and quantitatively similar to those of natural systems is also unclear. It would be astonishing if agricultural systems could replace all ecosystem services lost when the natural system was initially replaced. For good management, however, robust evidence, rather than assumptions, is needed.

BIOCULTURAL RESTORATION: INCLUDING THE ENTIRE RESTORATION PROCESS

To compensate for the rate of global environmental destruction, ecological restoration must be carried out in a landscape context wherever possible. The reasons for doing this are persuasive: 1. Large systems are more likely to be self-maintaining than fragments of systems. 2. Economies of scale are present in ecological restoration just as they are in many other activities. 3. Large ecological restoration activities are likely to generate more publicity than restoration of small fragments or patches and thus be protected from future damage because of increased public awareness. 4. Patch dynamics (e.g. shift of a patch from a source or a sink of a particular species) function well at the landscape level but not as well at the fragment level (which might not even be large enough for a single effective patch). 5. Distribution of seeds and other propagules is more likely to be effective if an array of diverse habitats is available or if heterogeneous habitats at least have the potential to develop in the area being restored.

The most important reason for viewing restoration on the landscape level, however, rests within the source of the problem. Given the rate of human population increase and the concomitant increase in affluence, finding any terrestrial areas of the planet not markedly influenced by human society is difficult. As a consequence, no landscape level restoration will endure if undertaken without society's approval and support (2). Janzen (11) uses the term biocultural restoration to emphasize the importance of this relationship. Janzen discusses the sociological technology needed to integrate the Guanacaste National Park into Costa Rican society—education, apprenticeship, classes for students and teachers at all ages and levels in the society, and research to obtain more information to improve the education process.

Community-Initiated Restoration

Janzen's work emphasizes the need to involve human cultures in restoration efforts, as they are the glue that keeps these projects together. In fact, this social component is at the root of many restoration projects. Examples of community-initiated restoration are abundant, but they often are not fully credited within the scientific literature (examples can be found in the journal *Restoration and Management Notes*). Gameson & Wheeler (12) state that the deliberate restoration of the Thames estuary was solely for the benefit of human society. They note that, as early as 1620, the Bishop of London expressed hope that the cleaning of the river would follow in good time. The Mattole River watershed restoration efforts by citizens of northern California's Humboldt County were begun by about a dozen people residing in the watershed. They called themselves The Mattole Watershed Salmon Support Group (13) and initiated erosion control, reforestation, salmonid restoration, and habitat enhancement.

Plumas County, California, is the site of the Red Clover restoration, a joint project between a local electric utility and the state government (14). The project restored 30 hectares (ha) of meadow along Red Clover Creek, a stream severely impacted by generations of intensive logging and agricultural practices. The restoration efforts also reduced the sediment load of the stream by 1000 metric tons per year, allowing the continuing function of a hydroelectric power plant downstream. The effects of this one project have been far reaching in that a large portion of the community was involved and made aware of its dependence on local ecosystem services. The Richard W DeKorte Park in the Hackensack Meadowlands of New Jersey provides an example of a formerly ruined landscape now functioning as a natural remnant supporting the visits of thousands of schoolchildren each year (15). Protected from the underlying trash heap by a synthetic liner and 425 m^3 of topsoil, DeKorte now harbors over 260 species of birds, including the ruddy duck, which only nests in two other locations in the state.

The Kissimmee River Restoration

The partial restoration of the Kissimmee River in Florida is an excellent example of biocultural restoration. Although the Kissimmee River restoration demonstration project was carried out jointly by the South Florida Water Management District (SFWMD) and the US Army Corps of Engineers, the basic impetus was from concerned citizens who remembered the river the way it was before flood control measures converted it into a straight canal. Several Florida governors and the state legislature supported the community action to restore the river. Because of the demonstration project, the same organizations and, in many cases, the same local citizens who initially wanted only to restore the recreational value of the river recognized the value provided by the river's natural state. In this case, societal objectives were clearly defined; the meandering backwaters of a 75-km section were restored while appropriate engineering ensured the continuation of satisfactory flood control (16, 17). An excellent summary of the Kissimmee River restoration, from a variety of viewpoints, occupies an entire special issue of *Restoration Ecology*. This special issue is a notable contribution to the literature on restoration ecology, especially as it relates to designing and conceptualizing restoration projects. Although the restoration process is in its initial stages, it has been ongoing long enough to provide valuable insights.

Urban Area Restoration

Ecological restoration need not be excluded from the most dense human population centers. Perhaps the re-establishment of human society's interactions with natural systems through urban restoration is one of the best arguments for restoration activities. Arguably, the greatest value of such restoration is to diminish the impact of urban runoff and other stresses on natural systems that originate in urban areas by making the reintroduction of urban runoff, urban waste, etc into natural systems more compatible with the system's tolerance and assimilative capacity.

Several examples of urban restoration and its concepts can be taken from the urban planning literature. Van der Ryn & Cowan (18) note that city planning practice, as it developed in the early twentieth century, emphasized zoning new development into separate, single-use land zones for housing, industry, commerce, and recreation. In an attempt to explain this emerging urban perspective, they borrow the term ecotone from ecology to characterize a soft overlapping of substantially different regions, and they note that most urban design has been quite hostile to ecotones. Slack (19) quotes Peter Berg, who indicates that cities must identify the natural limits of ecosystems and put themselves in balanced reciprocity with natural systems. He calls attention to the fact that restoration of a portion of a downtown creek in San Luis Obispo, California, enhanced both property values and economic activity. In some areas, not only will ecological restoration be extremely difficult, but preserving any sort of green belt, or natural zone adjacent to cities, will probably require extraordinary political skill. The city of Aurora, Colorado, for example, experienced approximately 900% growth over a 30-year period (20). With this kind of expansion, a readdressing of the relationship between urban areas and natural systems must be a priority.

The fact that ecosystems with some valuable ecological attributes exist at all in such heavily urbanized areas as the Netherland's Amsterdam Bos (a city park) and Central Park in New York City indicates that ecological restoration in urban areas should be not only possible but also useful to society. The Netherlands has pioneered both urban "wilds" and the ecological restoration component of landscape planning (21). As Barlow (21) notes, Delft Zuid is an urban wild intended and designed to provide a normally regimented people with daily contact with natural systems. For those who feel that ecological restoration in urban areas could only be accomplished by destroying presently used buildings and other artifacts, Stein (22) indicates that thousands of vacant and abandoned properties exist across the country, which could be used as community land trusts.

Particularly applicable to urban restoration is Falk's (23) idea that, unlike the restoration of great works of art and literature, ecological restoration is not intended to preserve a static entity but to protect and nurture nature's capacity for change. In urban areas with their associated levels of ecological manipulation, this capacity for change and adaptation is both highly necessary and difficult to maintain.

RESTORATION ECOLOGY: THE DEVELOPMENT OF A DISCIPLINE

As the relationship between human society and natural systems has developed and come under scrutiny over the past several decades, the science of restoration ecology has also progressed to the point that a dedicated journal, *Restoration Ecology,* was initiated by the Society for Ecological Restoration in 1992. Bradshaw (24) has stated that restoration ecology is the acid test for understanding ecosystems. A desire for such understanding may be the root of scientific interest in ecological restoration, given that community and ecosystem level ecological theories are perhaps best tested in an ecosystem reconstruction context (25). Others have raised ethical concerns about whether humans have the right to manipulate nature for their own ends (26). Nonetheless, restoration ecology is a broadening field and continues to produce many interesting results.

Facilitative Succession

As stated above, the social context implicit in restoration ecology requires specific study methods and concerns. However, a large portion of restoration is, and must be, firmly rooted in ecology. The connection between ecological succession and ecological restoration is the most obvious relationship between restoration and ecology (Table 3). Facilitative succession provides a useful perspective from which to view most restoration projects. The natural turnover of species communities over time provides the model that restoration ecologists attempt to mimic and accelerate. Succession theories can provide important perspectives for developing restoration plans. However, most theories have been developed using a small number of natural systems, mostly temperate hardwood forests. This research bias must be taken into account when using these theories. Luken (27) has produced a highly useful book that combines successional theory with management techniques while providing a good overview of the interactions between ecological theory and application.

Table 3 Applications of ecological succession theories in restoration ecology

Successional theory	Restoration implications	References
Relay floristics	Generally accepted to be a poor representation of succession; provides a model for introducing secondary successional species	27, 95
Initial floristics	Can guide design of revegetation strategies; stresses the importance of soil seed bank preservation	96
Facilitation	Identifying primary successional species responsible for improving conditions for secondary species	28, 97
Inhibition	Identifying primary successional species that hinder or halt secondary succession	28
Combination/contingency	Can guide management concerning site availability, colonizer availability, and colonizer performance; emphasizes a long-term, process-oriented approach to restoration	27, 31, 36

In many respects, Connell & Slatyer's (28) facilitation/inhibition dichotomy offers the most useful successional framework for restoration. The depletion of vesicular-arbuscular mycorrhizal (VAM) fungi in disturbed areas is an excellent example of identifying and removing specific, important blockages toward continued succession. Cuenca & Lovera (29) documented the depletion of VAM fungi in southern Venezuelan soils disturbed by road building. They subsequently showed initial colonization of the site by nonmycotrophic species, the presence of which could maintain the depressed VAM population and decrease chances of recolonization by native (mycorrhizal forming) species. The study showed that some revegetation strategies increased the VAM inoculum, suggesting techniques for partially alleviating this problem.

In an example of how initial colonization is sometimes the most important facilitation step, Franson & Bernath (30) have produced research showing that substantial numbers of plants from a site scheduled for mining could be retained for restoration activities elsewhere. The mining (the Viceroy Golds Castle Mountain Project in the East Mojave National Scenic Area, 96 km south of Las Vegas) will affect 360 ha of vegetation at the mine site itself and an additional 10 ha of land on the access route to the mine. The highly xeric conditions make initial colonization of disturbed areas extremely difficult. To address this problem, more than 11,000 plants from 15 plant species were salvaged from approximately 121 ha and placed in nurseries. These were maintained in nurseries until they were used for revegetation. Additionally, topsoil (referred to in the Victory Golds Castle Mountain Project research as growth media because of the lack of a discernible horizon in the soils in the mine area) was stockpiled for use in revegetation. Many of the plants were categorized as being in excellent to good condition, and the overall mortality by 1993 was about 9%. Although the success of this project cannot yet be fully judged, this design ensures that the revegetation will be plants that grew at the site before disturbance, or in a similar site elsewhere, and will maintain ecological capital. This strategy is commendable and deserves more attention at other sites where ecological disturbance is anticipated.

In many situations, restoration or succession is contingent on stochastic factors such as site availability and colonizer source (31). Robinson et al (32, 33) provide an excellent example of how facilitated colonization can be used in restoration. They conducted studies on the Fresh Kills Landfill in Staten Island, New York, to test the practicality of using woody species for reclamation. Fourteen years after the initial planting of 190 trees, they found that the planted species had not spread, but a wide variety of native invading species had colonized throughout the plantation. Further study revealed that the initial planting provided roosting points for birds and provided bird-dispersed native plant species with a colonization opportunity. These data suggest that subsequent colonization should be taken into account in decisions about tree plantings on similar sites so that the likelihood of further economical reforestation of native species by bird dispersal will be increased.

On arid lands where primary plant succession is hindered by extremes in heat and by drought, careful consideration of microhabitat can lead to successful colonization and recovery. Whisensant et al (34) created microcatchments to concentrate available moisture and facilitate the establishment of planted woody shrubs. This practice provided a site that eventually allowed colonization of native invading species among the shaded microcatchments.

By focusing on successional processes, restoration ecologists can use ecological theory to better design restoration plans. As their design is improved, restoration activities can be used to test these theories and develop new viewpoints.

Frames of Reference: What Should Be Restored?

Perhaps the most pressing problem in studying the recovery of a disturbed area is determining the frames of reference. This problem is inherent in defining both the term restoration and the goals of a restoration project. The predisturbance state of an area is often unknown, because most disturbance events are not preceded by thorough ecological surveys (35). For many ecosystems, such as the tall grass prairie of the Great Plains, it is difficult to find any of the predisturbance ecosystem. Furthermore, such predisturbance states are usually unattainable owing to the dynamic state of natural systems; vegetative and faunal communities constantly change over time, so the complexity of events that precipitated a particular condition can never be reconstructed (36). Therefore, most restoration projects pursue an approximation of predisturbance condition that is congruent with the current surrounding landscape.

Aronson et al (37) stress the importance of selecting some reference area, however imperfect, to facilitate baseline studies and the monitoring of success, which can be accomplished largely by the use of similar site comparisons and chronosequence studies. Holl & Cairns (38) worked in reclaimed coal surface mine lands of the southeastern United States to compare vegetational communities on reclaimed and undisturbed areas. Their findings show that, 30 years after reclamation, the disturbed sites carried only 48% of the plant species found in the undisturbed hardwood sites, and vegetational structure had not recovered to the mean tree basal area—undisturbed sites had more than twice that of the oldest mined sites. Bhatt & Soni (39) showed similar results for the vegetation on reclaimed rock phosphate mines in India, but they documented that the ant community returned to similar density and diversity after only 8 years. Other invertebrates have shown a similar response to reclamation (40). Thus, comparisons of the rate of return of various ecosystem components to approximate predisturbance condition are highly dependent on which component of the system is studied; however, such studies can be useful when certain components are of particular concern for restoration goals (e.g. vegetative structure).

Aronson et al (41, 42) move beyond single component comparisons for judging restoration efficacy. They use a matrix of measurements documenting the structural and functional recovery of disturbed systems. This synthetic approach incorporates measures, called vital ecosystem attributes, of current and potential future plant structure, faunal relationships, soil condition, water and nutrient availability, and microsymbiont effectiveness to create a more inclusive picture of the recovering landscape. This comprehensive strategy increases the monitoring demands for a restoration project, but it also approaches the problem from a holistic viewpoint, similar to the use of multiple analyses for diagnosing a patient's medical condition. This strategy also markedly increases the monitoring resolution, allowing the detection and correction of unsatisfactory conditions earlier. The use of such an integrative system provides the opportunity to observe key recovery processes and deduce methods to facilitate them.

CASE STUDIES

Selected case histories are presented here to demonstrate the state of the art of restoration ecology. The divisions are only for the convenience of the reader, as restoration projects often take both aquatic and terrestrial considerations into account. Each area discussed could easily be the subject of a dedicated review of its own. Therefore, we create a conceptual road map, rather than an exhaustive review, so all types of restoration ecology can be included.

Restoration in Aquatic Areas

Aquatic systems, specifically rivers and lakes but also marine systems, have long served to reduce the cumulative impacts of human activities by transporting pollutants away from the source. They provide an excellent example of ecosystem services that have been overwhelmed and therefore need to be augmented with technological services. As human pollutants became more industrially derived, the ability to assimilate the waste through biological activity was quickly overcome and highly polluted waters became widespread. Not until the advent of wastewater treatment technology in this century was water quality markedly improved. Balancing such economically important services with other functions of healthy aquatic systems is the main activity of restoration ecologists, and it exemplifies the difficult social and scientific problems restoration ecologists must face. Due to its economic and social importance, the restoration of lakes and rivers has received much attention in the literature. The 1992 NRC (2) volume provides an exhaustive discussion of restoration considerations, goals, and needs and contains several examples of the difficulties, as well as the successes, of aquatic restoration. In addition, Cooke et al (43) have produced the second edition of their book on lake and river restoration. This practical manual is often the best starting point for any aquatic restoration consideration.

Many factors contribute to short recovery times in aquatic systems. Yount & Niemi (44) document four characteristics underlying this trend: 1. Life history characteristics allow rapid recolonization and repopulation of affected areas. 2. Unaffected upstream and downstream areas are available and accessible, and internal refugia serve as sources of organisms for recolonization. 3. High flushing rates of lotic systems allow for the quick dilution or replacement of polluted waters. 4. Lotic systems are naturally subjected to a variety of disturbances, and the biota have evolved life history characteristics that favor flexibility or adaptability. Because of these features, the removal of particular human stresses often leads to the autogenic restoration of system quality. Such restoration can also apply to lentic systems such as lakes and reservoirs. By 1963, effluent from eleven Seattle, Washington, sewage treatment plants was being discharged into Lake Washington, producing accelerated nutrient enrichment and blue-green algae blooms (45). The diversion of this effluent into Puget Sound provided water clarity exceeding pre-1950 standards within 10 years.

However, restoration of water quality in lake ecosystems cannot be seen as complete restoration. Other human impacts, including acute toxification, overfishing, and exotic introductions, create more difficult problems. Lake Michigan has experienced a dramatic recovery of water quality since nutrient enrichment has been curtailed and closely monitored. However, the ancestral char and coregonines were nearly entirely displaced owing to invasion by the sea lamprey (46, 47). Stocking of the lake with exotic salmon species has restored the lake's sportfishing industry but has not succeeded in re-creating any sort of stable food web within the lake ecosystem (48). Organochlorine pollutants also provide an ongoing threat to the biological dynamics (49). Examples such as Lake Michigan serve as reminders of the complex nature of ecological systems and the necessity for integrative approaches towards restoration.

River and stream restoration often centers around reconstruction of fluvial geomorphology, as already shown by the Kissimmee River example, and restoration of ancestral flow rates altered by reservoir construction. Manipulation of instream structure aims to restore fish habitat, reduce sediment load, reconstruct streambed substrate, and establish natural sinuosity and energy distributions. Such projects have met with success when aimed at re-establishing sport fisheries and aesthetic conditions (50). However, larger rivers present greater difficulties because of the drastic manipulation of flows by dam and reservoir construction (51). Gore & Shields (52) discuss these difficulties and others, including reducing floodplain by levees, altering natural riparian habitat, and reducing total water surface area. Their comparison of small stream and large river restoration engineering demonstrates the problems of scale that must be dealt with on large river systems (e.g. weir construction, substrate quality improvement, meander reconstruction). Ligon et al (53) discuss methods of lessening the need for drastic restorative measures by designing dams to reduce the downstream geomorphology, which is at the root of the ecological changes. Restoration of stream flow is crucial for river and stream restoration. "If the stream's physical foundation is pulled out from under the biota, even the most insightful biological research program will fail to preserve ecosystem integrity" (53, p. 190).

Wetland Restoration

Less dynamic aquatic systems such as swamps and marshes offer a greater restoration challenge. This challenge is ever more important because over 50% of all wetland acreage in the continental United States has been lost (2). In areas where existing wetlands are impacted but salvageable, successes have resulted mainly from removing specific stresses and relinking hydrological connections

(54). In many other areas, and as a result of US Environmental Protection Agency regulations mandating mitigation of further wetland destruction, artificial wetland construction is meeting with mixed results (55). Efforts to increase diversity and biotic functioning of impacted areas have been successful to a degree; however, most constructed wetlands do not show high similarities to natural systems, owing to such problems as hydrology and hydrophyte colonization (56). This lack of similarity between constructed and natural systems must be taken into account when making policy decisions on further wetland destruction.

However, our inability to fully re-create natural wetland environments should not negate the value of wetland creation, for two reasons. First, as in all restoration situations, the project aims are not to fully create a natural system but, instead, to provide the material and situation from which nature can heal itself. Nearly all created wetlands will require many more years before the natural world can fully shape them into “natural” forms. Second, created wetlands can perform many of the services that natural wetlands provide. Flood protection, wildlife habitat, and waste treatment are all valid reasons for restoring destroyed wetland acreage (57–60).

Perhaps the most visible wetland restoration undertaking to date is the concerted effort to restore the Florida Everglades ecosystem. The Everglades system has been substantially altered through hydrological alteration since the mid-1800s. The 1994 book *Everglades, the Ecosystem and Its Restoration* (60a) provides an excellent in-depth survey of the abiotic, biotic, social, and economic considerations that are involved in the large-scale restoration.

Coastal and Marine Restoration

Coastal beaches present an interesting situation for restoration ecologists. Beach locations are highly attractive for recreational purposes, which increases the number of condominiums, hotels, summer dwellings, and the like. Beaches are also essential storm barriers. Possibly most important from a management standpoint is the fact that beaches are dynamic, and they usually diminish in winter and accrete in summer. Many beaches are eroding naturally, and their positions are moving shoreward over time. The problem is that, once expensive dwellings and other human artifacts are placed on beaches, there is a cry to protect them and efforts are made to manage the shoreline to satisfy socioeconomic needs. Protection usually takes the form of fixed structures, such as sea walls, groins, and breakwaters, which create barriers between land and sea. These structures disrupt the along-shore transport of sediments; they alter deposition of sand and other particulate matter, often exacerbating erosional problems. In many places, attempts to offset the erosion are made with “beach nourishment”—adding sand to extend the beach and the near-shore shallows seaward. This procedure has gained acceptance in the United States, Europe, Australia, and parts of Japan. In Japan, sediments from Lake Biwa have been used to nourish certain beaches (S Matsui, personal communication). As might be expected, the tactic of beach nourishment has both strong opposition and strong support. Some nourishment projects appear to have been successful, whereas others have not met expectations. The NRC (61) stresses the importance of applying engineering principles and technology to establish the physical conditions essential for enhancement or restoration and to assist in recolonization. As Orth et al (62) have shown, the limited seed dispersal capabilities of marine macrophytes underscore the need for dispersal facilitation to achieve restoration goals.

Restoration of oceanic habitats has received less attention than restoration of other components of the biosphere. Much of the literature on oceanic habitats deals with the problem of overfishing and deep sea pollution (63). However, creative applications of theory and technology have produced possibilities for successful restorations. Tegner (64) uses the concept of refugia to address the rebuilding of decimated Southern California abalone stocks. He showed that to meet this goal refugia design must consider the life history of target species, the oceanographic regime and distances from source areas, and the feasibility of enforcement. Another example comes from Guzman (65), who addresses the problem of accelerated coral reef destruction caused by increased marine traffic and poor seamanship. Guzman has shown that coral fragment transplants have an 80% survival rate. Such viability suggests the feasibility of transplantation as a restoration tool for delicate and slow-growing coral communities (66).

Upland Restoration

Restoration of upland areas involves managing many of the most challenging components of restoration ecology. Exotic invasion, acute toxicity, desertification, nutrient deficiencies, soil depletion, and other factors can interact to create highly aberrant and recalcitrant disturbances. Land uses such as mining, agriculture, forestry, grazing, and landfilling are all necessary for today's society. However, the consequence of these land uses is often serious degradation that must be dealt with immediately and prevented in the future.

Surface mining constitutes a massive dislocation of terrestrial biota and has led to the development of a well organized reclamation community. Bradshaw (67) makes extensive use of case histories and examples to cover the problems encountered with this type of degradation. The main concern about surface mining is whether biologically suitable topsoil can be regenerated. Mine spoil varies widely with acidity (pH 3–8), parent rock type, extractable nutrients, soluble salts, and degree of weathering (68). These characteristics must be managed by topsoil amendments, topsoil addition, or topsoil creation (69). Revegetation of mined areas is dictated by a combination of the physical characteristics of the soil, the targeted postmining land use, governmental regulations, and financial constraints.

Nonsustainable forestry practices throughout the world have created a huge challenge to restoration ecologists. Newer silviculture techniques promise to reduce the negative impact of forestry; however, many problems remain from past foresting. Tropical deforestation duly garners the brunt of the popular media coverage because of the difficulty of regenerating such systems. Mineral-poor soils do not support rapid growth of new trees, and the associated structure of epiphytes and animals is extremely difficult to restore directly because of the lack of colonizing sources (70, 71). The most likely possibility for restoring such functions and structure is to use existing tropical forest fragments as colonizer pools and actively restore all possible interstitial areas (72, 73).

Restoration and Conservation

Restoration of scarce habitat types could, theoretically, save threatened and endangered species (74). However, evidence supporting this possibility is not robust. The early stages of ecological restoration are usually marked successional processes, probably characteristic of all early stages of ecosystem development, and they are significantly less diverse than the developmental stages of established, more stable ecosystems. However, restoration in this sense assumes that lost habitat for rare and endangered species can be replicated, either where similar habitats once existed or by creating suitable habitat where damage occurred to dissimilar habitat.

The main dilemma is obtaining colonizing species. Some rare and endangered species removed from their small pockets of suitable habitat for recolonization purposes might prove unsuccessful in the new habitat. Further, removal may result in a threat to the continued existence of the population on its remaining natural habitat. This problem is compounded by the fact that species-rich areas often do not coincide for different taxa, and many rare species do not occur within these species-rich areas (75). Thus, restoration efforts aimed at providing specific habitat near possible colonizing sources are difficult to design and may provide a low perceived benefit per unit effort. Griffith et al (76) found that translocation of threatened and endangered species results in self-maintaining populations only 46% of the time, as compared to an 86% success rate with game translocations. They also determined that a typical translocation involves six releases over a 3-year period. These spaced releases are carried out so that animals have an opportunity to adjust to their surroundings, establish stable populations, and then gradually increase their numbers. Franklin (77) suggests that, rather than focus on large vertebrates and single species reintroductions, the time, money, and effort should be spent instead on saving ecosystems and all the biodiversity therein. However, as Orians (78) notes, although preserving systems is a good idea, no legislation currently provides reliable protection for ecosystems, and developing such legislation will be difficult, both scientifically and politically. As Burnham & Cilek (79) note, a caveat in the Endangered Species Act indicates critical habitat should be protected in addition to individual species. Such protection would provide an ecological umbrella covering many species.

Even if this effort proves successful, the problem still exists of the relationship of this particular habitat to the larger, ecological landscape in which it occurs. The NRC (2) has stressed the desirability of restoring ecosystems so that they are self-maintaining or self-perpetuating and maintain their own normal successional processes, variability, etc. Therefore, restoring a particular habitat to meet the highly specific needs of a particular endangered or threatened species may be contrary to more encompassing restoration goals. In spite of this complication, evidence shows large-scale restoration projects benefit rare and endangered species. Restoration of pine-grassland communities in the Ouachita National Forest, Arkansas, has been shown to be beneficial to neotropical migrant birds, including the endangered eastern woodpewee, as well as declining species, such as the red-cockaded woodpecker (80). Such examples reinforce the value of restoration projects at all levels, even in cases in which theory does not currently predict benefits.

RESTORATION ECOLOGY: THE CALL FOR OBJECTIVES AND CRITERIA

Restoration ecology is a relatively young field and, because the success of many ecological restoration activities may not be known for many decades or even centuries, very explicit statements of what is intended for each restoration project are needed so that the degree of success or failure can be determined on a site-specific basis. Any restoration plan should therefore be accompanied by an explicit statement of criteria for success and failure that will permit rigorous examination of the activity itself and, equally important, identify changes in strategy more likely to reach intended goals. Moreover, considering the current rate of modification in all natural systems, wide-ranging restoration objectives must be developed with the aim of ameliorating past, present, and future damage. Although research continues throughout the field, explicit objectives and criteria do not exist for all restoration situations (Table 4). Efforts such as those coordinated by the Society for Ecological Restoration are to be commended and should be used as a model for all restorationists (81).

In the literature, other fields dealing with the interactions between human and natural systems, specifically conservation biology, have been deemed “crisis

Table 4 Examples of restoration objectives and criteria

Scale of goal	Example objective or criteria	References
Objectives	Restoration of wetlands to offset any further loss	2
	Overall gain of 4 million ha of wetlands in the United States by the year 2010	
	Restoration of 640,000 km of rivers and streams in the United States by the year 2010	
Criteria	Standardization of restoration plans	81
	Exotic species management	
	Integration of ecological restoration with surrounding landscape and local stewardship	

disciplines" because they address urgent issues (82). Perhaps restoration ecology, with its equal footings in social and natural science that make its very definition a difficult task, is the greatest crisis discipline of all. Restoration ecologists must take it upon themselves to identify the factors necessary for restoration of ecosystems, rigorously examine the actual activity of restoration, evaluate restoration efficacy, and develop specific methodologies for the discipline. These activities must be undertaken to further restoration ecology's continued development into a robust and productive scientific field.

ACKNOWLEDGMENTS

We are indebted to LB Maddox for transcribing the dictation of this manuscript; to BR Niederlehner, PA Turner, and ACP Heaton for reading the first drafts; and to D Donald for editorial assistance. Mobil Foundation supplied funds that made preparation of this review possible.

Literature Cited

1. Boyden S. 1992. *Biohistory: The Interplay Between Human Society and the Biosphere, Past and Present*, Ser. ed. JNR Jeffers. Paris: Man Biosphere Ser., UNESCO. 265 pp.
2. National Research Council (NRC). 1992. *Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy*. Washington, DC: Natl. Acad.
3. Jackson LL, Lopoukhine N, Hillyard D.

1995. Ecological restoration: a definition and comments. *Restor. Ecol.* 3(2):71–75

4. Ludwig D, Hilborn R, Walters C. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. *Science* 260:17–36
5. Cairns J Jr. 1996. Determining the balance between technological and ecosystem services. In *Engineering Within Ecological Constraints*, ed. PC Schulze, pp. 13–30. Washington, DC: Natl. Acad.
6. Avise JC. 1994. The real message from Biosphere 2. *Conserv. Biol.* 8(2):327–29
7. Westman WE. 1977. How much are nature's services worth? *Science* 197:960–64
8. Cairns J Jr. 1993. Maintaining per capita ecosystem services while the human population grows to ten billion: a major global challenge for biologists. *Assoc. Southeast. Biol. Bull.* 40(3):159–63
9. Van Wilgen BW, Cowling RM, Burgers CJ. 1996. Valuation of ecosystem services. *BioScience* 46(3):184–89
10. Wilson EO, ed. 1988. *Biodiversity*. Washington, DC: Natl. Acad.
11. Janzen DH. 1988. Guanacaste National Park: tropical ecological and biocultural restoration. In *Rehabilitating Damaged Ecosystems*, ed. J Cairns Jr, II:143–92. Boca Raton, FL: CRC
12. Gameson ALH, Wheeler A. 1977. Restoration and recovery of the Thames Estuary. In *Recovery and Restoration of Damaged Ecosystems*, ed. J Cairns Jr, KL Dickson, EE Herricks, pp. 72–101. Charlottesville: Univ. Press Va.
13. House F. 1990. To learn the things we need to know. *Whole Earth Rev.* 66:37–47
14. Hamilton J. 1993. Streams of hope. *Sierra* Sept./Oct:98–104, 121–22
15. Griswold M. 1993. The landfill's purpose. *Landsc. Arch.* Oct:78–95
16. Loftin KA, Toth LA, Obeysekena JTB. 1990. *Kissimmee River Restoration: Alternative Plan Evaluation and Preliminary Design Report*. Palm Beach: South Fla. Water Manage. Dist.
17. Toth LA. 1990. Impacts of channelization on the Kissimmee River Ecosystem. *Kissimmee River Restor. Symp., Oct., 1988*. West Palm Beach: Sci. Div., South Fla. Water Manage. Dist.
18. Van der Ryn S, Cowan S. 1993. Healthy building: toward regenerative architecture. *Ann. Earth* 11(2):24–27
19. Slack G. 1994. Emerald cities: visions or hallucinations? *Pac. Disc.* 47(2):27–33
20. Pyle RM. 1993. *The Thunder Tree: Lessons from an Urban Wildland*. Boston: Houghton Mifflin. 220 pp.
21. Barlow E. 1981. Urban wilds. In *Urban Open Spaces*, ed. L Taylor, pp. 118–19. New York: Rizzoli Int. Publ.
22. Stein PR. 1981. Neighborhood land trusts. In *Urban Open Spaces*, ed. L Taylor, pp. 114–15. New York: Rizzoli Int. Publ.
23. Falk D. 1990. Discovering the future operating the past: some reflections on restoration. *Restor. Manage. Notes* 8(2):71–72
24. Bradshaw AD. 1983. The reconstruction of ecosystems. *J. Appl. Ecol.* 20:1–17
25. Jordan WR III, Gilpin ME, Aber JD. 1987. *Restoration Ecology*. New York: Cambridge Univ. Press
26. Cowell MC. 1993. Ecological restoration and environmental ethics. *Environ. Ethics* 15:19–32
27. Luken JO. 1990. *Directing Ecological Succession*. London: Chapman & Hall
28. Connell JH, Slatyer RO. 1977. Mechanisms of succession in natural communities and their role in community stability and organization. *Am. Nat.* 111:1119–44
29. Cuenca G, Lovera M. 1992. Vesicular-arbuscular mycorrhizae in disturbed and revegetated sites from La Gran Sabana, Venezuela. *Can. J. Bot.* 70:73–79
30. Franson RL, Bernath G. 1993. Health of plants and soil salvaged for revegetation at a Mojave desert gold mine. In *The Challenge of Integrating Diverse Perspectives in Reclamation,* 1:325–28. Spokane: 10th Natl. Meet., Am. Soc. Surf. Min. Reclam.
31. Pickett STA, Collins SL, Armesto JJ. 1987. Models, mechanisms and pathways of succession. *Bot. Rev.* 53:335–71
32. Robinson GR, Handel SN. 1993. Forest restoration on a closed landfill: rapid addition of new species by bird dispersal. *Conserv. Biol.* 7(2):271–78
33. Robinson GR, Handel SN, Schmalhofer VR. 1992. Survival, reproduction and recruitment of woody plants after 14 years on a reforested landfill. *Environ. Manage.* 16(2):265–71
34. Whisensant SG, Thurow TL, Maranz SJ. 1995. Initiating autogenic restoration on shallow semiarid sites. *Restor. Ecol.* 3(1):61–67
35. Cairns J Jr. 1991. Is restoration to predisturbance condition a viable option? *Environ. Prof.* 11:152–59
36. Pickett STA, Parker VT. 1994. Avoiding the old pitfalls: opportunities in a new discipline. *Restor. Ecol.* 2(2):75–79
37. Aronson J, Dhillion S, Le Floc'h E. 1995. On the need to select an ecosystem of reference, however imperfect: a reply to

Pickett and Parker. *Restor. Ecol*. 3(1):1–3

38. Holl KD, Cairns J Jr. 1994. Vegetational community development on reclaimed coal surface mines in Virginia. *Bull. Torrey Bot. Club* 121(4):327–37
39. Bhatt V, Soni P. 1992. Revegetation and ant colonization relationships in reclaimed rock phosphate mines. *Trop. Ecol*. 33(2):223–30
40. Hutson BR. 1990. Colonization of industrial reclamation sites by acari, collumbola and other invertebrates. *J. Appl. Ecol*. 17:255–75
41. Aronson J, Floret C, Le Floc'h E, Ovalle C, Pontanier R. 1993. Restoration and rehabilitation of degraded ecosystems in arid and semi-arid lands. Case studies in Southern Tunisia, Central Chile and Northern Cameroon. *Soc. Ecol. Restor*. Sept:168–87
42. Aronson J, Floret C, Le Floc'h E, Ovalle C, Pontanier R. 1993. Restoration and rehabilitation of degraded ecosystems in arid and semi-arid lands; I: a view from the South. *Soc. Ecol. Restor*. Mar:8–17
43. Cooke GD, Welch EB, Peterson SA, Newroth PR. 1993. *Restoration and Management of Lakes and Reservoirs.* Boca Raton, FL: Lewis. 548 pp.
44. Yount DJ, Niemi GJ. 1990. Recovery of lotic communities and ecosystems from disturbance—a narrative review of case studies. *Environ. Manage*. 14(5):547–69
45. Edmondson WT. 1991. *The Uses of Ecology: Lake Washington and Beyond*. Seattle: Univ. Wash. Press. 312 pp.
46. Christie WJ. 1974. Changes in the fish species compositions of the Great Lakes. *J. Fish. Res. Bd. Can*. 31:827–54
47. Kitchell JF. 1990. The scope for morality caused by sea lamprey. *Trans. Am. Fish. Soc*. 119:642–48
48. Kitchell JF, Crowder LB. 1986. Predator-prey interactions in Lake Michigan: model predictions and recent dynamics. *Environ. Biol. Fish*. 16:205–11
49. Eisenreich SJ, Wong C, Golden K, Jeremiason J, Hallgren J, et al 1993. Spatial and chronological distribution of organochlorines and PAHs in Great Lakes' sediments. *36th Conf. Int. Assoc. Great Lakes Res., DePere, WI.* 136 pp.
50. Crispin V, House R, Roberts D. 1993. Changes in instream habitat, large woody debris and salmon habitat after the restructuring of a coastal Oregon stream. *N. Am. J. Fish Manage*. 13(1):96–102
51. Gup T. 1994. Dammed from here to eternity: dams and biological integrity. *Trout* 35:14–20
52. Gore JA, Shields FD. 1995. Can large rivers be restored? *BioScience* 45:193–203
53. Ligon FK, Dietrich WE, Trush WJ. 1995. Downstream ecological effects of dams. *BioScience* 45:183–92
54. Weller MW. 1995. Use of two waterbird guilds as evaluation tools for the Kissimmee River restoration. *Restor. Ecol*. 3(3):211–24
55. Beck RE. 1994. The movement in the United States to restoration and creation of wetlands. *Nat. Resour. J*. 34(4):781–822
56. Mendelson J, Aultz SP, Mendelson JD. 1992. Carving up the woods: savannah restoration in Northeastern Illinois. *Restor. Manage. Notes* 19(2):127–31
57. Hey DL, Philippi NS. 1995. Flood reduction through wetland restoration: the upper Mississippi river basin as a case history. *Restor. Ecol*. 3(1):4–17
58. Mitsch WJ, Van der Valk A, Jaworski E. 1994. Wetland restoration at a former Nike missile base in the Great Lakes basin. *Restor. Ecol*. 2(1):31–42
59. White GC, Smalls IC, Bek PA. 1994. Carcoar Wetland—A wetland system for river nutrient removal. *Water Sci. Tech*. 29(4):169–75
60. Hamilton H, Nix PG, Sobolewski A. 1993. An overview of constructed wetlands as alternatives to conventional waste treatment systems. *Water Pollut. Res. J. Can*. 28(3):529–48

60a. Davies SM, Ogden JC. 1994. *Everglades: The Ecosystem and Its Restoration.* Del Ray Beach, FL: St. Lucie Press

61. National Research Council (NRC). 1994. *Restoring and Protecting Marine Habitat: The Role of Engineering and Technology*. Washington, DC: Natl. Acad.
62. Orth RJ, Luckenbach M, Moore KA. 1994. Seed dispersal in a marine macrophyte: implications for colonization and restoration. *Ecology* 75(7):1928–39
63. Saldahna L. 1992. Marine fishes, habitat and conservation. *Netherlands J. Zool*. 42(2–3):190–99
64. Tegner MJ. 1993. Southern California abalones: Can stocks be rebuilt using marine harvest refugia? *Can. J. Fish. Aquat. Sci*. 50(1993):2010–19
65. Guzman HM. 1991. Restoration of coral reefs in Pacific Costa Rica. *Conserv. Biol*. 5(2):189–94
66. Purjava GR, Remesh R. 1993. Ecology, conservation and restoration of coral reef ecosystems. In *Sustainable Management*

of Coastal Ecosystems, ed. MS Swaminathan, R Ramesh, pp. 103–13. Madras, India: Swaminathan Res. Found.

67. Bradshaw AD. 1984. Land restoration: now and in the future. *Proc. R. Soc. London Ser. B* 223:1–23
68. Daniels WL, Zipper CE. 1995. Improving coal surface mine reclamation in the central Appalachian region. In *Rehabilitating Damaged Ecosystems*, ed. J Cairns Jr, pp. 187–218. Boca Raton, FL: Lewis
69. Pichtel JR, Dick WA, Sutton P. 1994. Comparison of amendments and management practices for long-term reclamation of abandoned mine lands. *J. Environ. Qual*. 23(4):766–72
70. Montagnini F, Fanzeres A, Guimaraes Da Vinha S. 1994. Studies on restoration ecology in the Atlantic forest region of Bahia, Brazil. *Interciencia* 19(6):323–30
71. Handel SN, Robinson GR, Beattie AJ. 1994. Biodiversity resources for restoration ecology. *Restor. Ecol*. 2(4):230–41
72. Veitch N, Webb NR, Wyatt BK. 1995. The application of geographic information systems and remotely sensed data to the conservation of heathland fragments. *Biol. Conserv*. 72(1):91–97
73. Janzen DH. 1991. How to save tropical biodiversity. *Am. Entomol*. Fall:159–71
74. Cairns J Jr. 1988. Increasing diversity by restoring damaged ecosystems. In *Biodiversity*, ed. EO Wilson, pp. 333–43. Washington, DC: Natl. Acad.
75. Prendergast JR, Quinn RM, Lawton JH, Eversham BC, Gibbons DW. 1993. Rare species, the coincidence of diversity hotspots and conservation strategies. *Nature* 365:335–37
76. Griffith B, Scott M, Carpenter JW, Reed C. 1989. Translocation as a species conservation tool: status and strategy. *Science* 45:477–80
77. Franklin JF. 1993. Preserving biodiversity: species, ecosystems, or landscapes. *Ecol. Appl*. 3(2):202–5
78. Orians GH. 1993. Endangered at what level? *Ecol. Appl*. 3(2):206–8
79. Burnham WA, Cilek J. 1994. The Peregrine Fund: giving wings to recovery. *Endanger. Species Tech. Bull*. 19(2):6–9
80. Wilson CW, Masters RE, Bukenhofer GA. 1994. Breeding bird response to pine-grassland community restoration for red-cockaded woodpeckers. *J. Wildl. Manage*. 59(1):56–67
81. Society for Ecological Restoration. 1994. Issues and activities pertinent to the restoration community. *Restor. Ecol*. 2(2): 132–33
82. Doak DF, Mills LS. 1994. A useful role for theory in conservation. *Ecology* 75(3):615–26
83. Ehrlich PR, Mooney HA. 1983. Extinction, substitution and ecosystem services. *BioScience* 33(4):248–52
84. Hitzhusen FJ. 1993. Land degradation and sustainability of agricultural growth: some economic concepts and evidence from selected developing countries. *Agric. Ecosyst. Environ*. 46:69–79
85. Izac AMN, Anaman KA, Jones R. 1990. Biological and economic optima in a tropical grazing ecosystem in Australia. *Agric. Ecosyst. Environ*. 30:265–79
86. Vitousek PM. 1994. Beyond global warming: ecology and global change. *Ecology* 75(7):1861–76
87. Gren IM, Groth KH, Sylven M. 1995. Economic values of Danube floodplain. *J. Environ. Manage*. 45(4):333–45
88. Cairns J Jr. 1995. The case for ecosystem services as toxicological endpoints. *Hum. Ecol. Risk Assess*. 1(3):171–74
89. Culotta E. 1995. Bringing back the Everglades. *Science* 268:1688–90
90. Gottfried RR. 1992. The value of a watershed as a series of linked, multiproduct assets. *Ecol. Econ*. 5(2):145–61
91. Davis GW, Midgley GF, Hoffman MT. 1994. Linking biodiversity to ecosystem function: a challenge to fynbos ecology. *S. Afr. J. Sci*. 90(6):319–21
92. Lugo AE. 1995. Management of tropical biodiversity. *Ecol. Appl*. 5(4):956–61
93. Callicott JB. 1991. The wilderness idea revisited: the sustainable development alternative. *Environ. Prof*. 13:235–47
94. Power TM. 1991. Ecosystem preservation and the economy in the greater Yellowstone area. *Conserv. Biol*. 5(3):395–404
95. Clements FE. 1916. Plant succession: an analysis of the development of vegetation. *Carnegie Inst. Washington Publ.* 242
96. Egler FE. 1954. Vegetation science concepts. I. Initial floristic composition—a factor in old-field vegetation development. *Vegetation* 4:412–17
97. Callaway RM. 1995. Positive interactions among plants. *Bot. Rev*. 61(4):306–41