Restoration Ecology: Interventionist Approaches for Restoring and Maintaining Ecosystem Function in the Face of Rapid Environmental Change

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Key Words

climate change, complex ecosystems, ecological restoration, priority setting, threshold

Abstract

Restoration ecology provides the conceptual and practical frameworks to guide management interventions aimed at repairing environmental damage. Restoration activities range from local to regional and from volunteer efforts to large-scale multiagency activities. Interventions vary from a "do nothing" approach to a variety of abiotic and biotic interventions aimed at speeding up or altering the course of ecosystem recovery. Revised understanding of ecosystem dynamics, the place of humans in historic ecosystems, and changed environmental settings owing to rapid environmental change all impact on decisions concerning which interventions are appropriate. Key issues relating to ecosystem restoration in a rapidly changing world include understanding how potentially synergistic global change drivers interact to alter the dynamics and restoration of ecosystems and how novel ecosystems without a historic analogue should be managed.

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INTRODUCTION

Restoration ecology is a relatively young science that aims to provide the scientific underpinnings to the management and repair of damaged ecosystems. The practice of ecological restoration is becoming an increasingly important tool in humanity's attempt to manage, conserve, and repair the world's ecosystems in the face of an increasing legacy of environmental damage (1, 2). The field has seen a dramatic increase in interest from academic ecologists in the past decade (3) as attempts are made to move toward a sound conceptual underpinning for the science (4–7). Such a conceptual framework allows for generalizations to be made from particular studies and restoration projects and for lessons learned in one place to be more readily transferred to other situations. Restoration is, by its nature, largely an interventionist activity. In the light of recent conceptual developments in restoration ecology, we discuss the different types of intervention that are used in restoration and then consider these activities in the context of ongoing rapid environmental change.

WHAT IS ECOLOGICAL RESTORATION?

Ecological restoration can be described as the process of assisting the recovery of damaged, degraded, or destroyed ecosystems (8). "Restoration" is one of a stable of "re" words that have come to be associated with some sort of environmental repair. Some of the more commonly used terms include: rehabilitation, reclamation, recreation, remediation, revegetation, and reconstruction. Allied terms also include ecological engineering (9).

Traditionally, restoration has been viewed primarily as a means to reset the ecological clock and return an ecosystem back to some past state, often what was there prior to disturbance or damage [e.g., (10, 11)]. Other activities that aim to repair damage, but not necessarily return the historic ecosystem, have been termed rehabilitation or, when an alternative system or land use is aimed at, reallocation (10). There is increasing recognition that many forms of repair activity are needed that cover a variety of aims, including restoring ecosystem function and services as well as particular sets of species (12). Hence, restoration covers a wide range of activities ranging from the purist perspective, which seeks to return an exact copy of the preexisting ecosystem and all its species to a degraded area, to less ambitious but no less worthy goals to return a degraded area to some sort of functioning ecosystem, to basic aims of returning some sort of vegetation for erosion control or food and fiber production.

There is a wide range of circumstances in which restoration is being attempted around the world. The scale of operation ranges from very local to regional and national, and the types of work undertaken vary from local volunteers working with hand tools to large industrial processes involving earthmoving machinery.

For instance, we see individuals and local communities in cities and rural areas engaging in restoration of local preserves, which have been invaded by aggressive nonnative weedy species, or waterways, which have been turned more into drains than living ecosystems. These activities are often very hands-on endeavors, engage people in voluntary repair of damaged ecosystems, and can engender a reconnection with nature, especially in urban environments [e.g., (11, 13, 14)]. Such activities can be highly successful in both ecological and social terms, and in some cases, a collection of local activities can be brought together to form broader restoration and conservation strategies and visions for a whole region (15).

In addition to these local restoration efforts, there are a great many projects run by communities, government agencies, and nongovernmental organizations (NGOs), which, for varied reasons, aim to restore either the structure or function (or both) of systems that have been degraded or modified to a greater or lesser extent. These projects range in size from a few hundred square meters to hundreds of thousands of square kilometers and include the following:

- Restoring fire and grazing regimes to prairie remnants in the Midwest of North America (16, 17)
- Restoring surface-mined areas in forests in southwestern Australia to return a forest ecosystem to the area and at the same time protect drinking water supplies and other functions essential in multiple-use forests (18)
- Restoring rainforest ecosystems in areas formerly deforested in Costa Rica, in order to increase the area of valuable habitat and at the same time provide important functions such as ensuring clean water supply (19, 20)
- Restoring woodland cover to large areas of Scotland, which have until recently been maintained as open areas for grazing and sport shooting by a landed elite, in order to both increase the area of an important ecosystem and wildlife habitat and to provide employment and opportunity for local communities (21)
- Restoring waterflows to the Mesopotamian Marshes in southern Iraq, which had been previously drained by the Hussein regime to displace marsh Arabs, in order to both restore the ecology of the wetlands and allow a people to return to their traditional way of life (22)
- Restoring plant cover in arid lands in Africa and elsewhere that have been degraded through overgrazing, overuse, or neglect during war and famine, in order to both stabilize the environment and provide livelihoods, food, and fuel for huge numbers of people (23–25)
- Restoring rivers and water flows in southern Florida to both allow for adequate flood control and feed the internationally important Everglades National Park (26, 27)
- Restoring fire regimes in forests in the western United States to both return the forest to a different structure and prevent continuing catastrophic forest fires (28, 29)

The above set of examples provides a flavor of the range of activities encompassed within restoration. **Table 1** indicates the types of intervention likely to be needed in each case, together with the types of people likely to undertake the restoration. Some involve very hands-on local action by enthusiastic and hard-working volunteers with a conservation focus. Others involve local people working to turn around decades of degradation to alleviate both environmental degradation and serious human deprivation. Others involve a much more mechanized approach with large machinery involved and work at very broad spatial scales: Many of these are multimillion dollar projects led by government. The scale of focus, resources available, and objectives vary greatly across this range. Most of these activities involve some sort of interventional management. In this review, we examine the different types of interventions used in restoration, using the projects listed above as illustrative examples.

Table 1 Examples of restoration projects conducted at local or regional scales, with representative examples of abiotic and biotic interventions[a]

Restoration project	Spatial scale	Abiotic interventions	Biotic interventions	Type of people involved	Degree of success[b]
Prairie remnants, Midwest United States	Local	• Reinstating historic fire regime	• Altering grazing intensities • Removal of nonnative shrub species	Community groups	Successful if ongoing management applied
Surface-mined lands in southwestern Australia	Local	• Soil ripping • Fertilizer addition	• Return of plant community via topsoil return, direct seeding, and planting • Control of herbivory	Mining company employees	Successful return of forest ecosystem subject to ongoing adaptive management
Rainforest in Central and South America	Local	—	• Addition of structural vegetation components	Community groups	Partial return of forest ecosystem, forest structure reestablished
Woodlands in Scotland	Local	• Reduction of fire frequency	• Control of grazing by deer and other herbivores	NGOs, community groups	Successful regeneration of tree species
Mesopotamian Marshes	Regional	• Reinstatement of water flows into marshes	—	National management body, local community	Successful rehydration of some areas; ecosystem response still developing
Arid lands (Africa and elsewhere)	Local/ regional	• Provision of physical barriers to slow water flow • Creation of microcatchments/ imprinting	• Reduction of grazing pressure	Local managers, community groups, NGOs	Successful redevelopment of woody vegetation and pasture in some areas
Rivers in southern Florida	Regional	• Removal of channelization and barrier gates • Reinstatement of river meanders	—	Regional management bodies	Successful local restoration of river reaches; success of broader regional project still to be determined
Fire regimes in southwestern United States	Regional	• Reinstatement of historic frequent low-intensity fire	• Structural alteration of vegetation to alter fuel distributions	State and federal agencies	Still to be determined

[a]See text for literature references for particular projects.

[b]Note: Success needs to be determined against the specific goals set for particular projects.

INTERVENTION: WHEN, WHERE, AND HOW MUCH?

Deciding on what type of intervention, if any, is required for the effective restoration of an ecosystem (or particular components or processes) presupposes a clear understanding of how the ecosystem works and what the outcomes of the intervention are likely to be. In other words, we need to understand how it worked before it was modified or degraded and then use this understanding to reassemble it and reinstate essential processes. It has been recently suggested that restoration often rests on a series of myths, which are based on assumptions regarding how systems work and what the outcome of particular interventions might be

(30). These myths relate to how predictable ecosystem dynamics are, how likely it is that different system components will return, and how possible it is to recreate past ecosystems. Moving beyond these myths is a key element of developing more successful restoration strategies. Ideas from succession theory and ecosystem assembly can be useful in this context (31, 32), and allowing normal successional processes to proceed may sometimes be the most effective way to return an ecosystem to a previous state. Where succession does not proceed along expected or desired trajectories, then intervention of some sort may be required (33, 34).

There is, however, increasing recognition that ecosystem dynamics can be complex, nonlinear, and often unpredictable (35–37). Hence, previously accepted ideas of gradual successional change may not be applicable in all situations (38). Of particular importance is the recognition that some ecosystems may occur in a number of alternative states, which may be contingent on the history of disturbance, human intervention, and other factors (39–41). Where positive feedback loops are involved, restoration of an undesirable ecosystem state to the desired ecosystem state may be difficult, requiring additional resources beyond where successional time is all that is needed.

The type of intervention required in restoration depends heavily on the type and extent of damage to the ecosystem. In some cases, relatively small changes to management or manipulation of the species composition are required (e.g., removal of harmful invasive species or replacement of missing species). In others, substantial alteration of the physical and/or chemical environment may be needed to restore ecosystem, landscape, or regional processes, such as hydrology and nutrient dynamics. The more degraded an ecosystem is, and the more fundamentally the basic ecosystem processes have been altered, the more difficult and expensive restoration will be.

Recently, attention has been focused on the importance of recognizing when ecological systems are likely to recover unaided (by autogenic processes) versus when they require active restoration efforts. This involves the identification of restoration thresholds, which are essentially barriers that prevent the recovery of degraded systems. These barriers can result from biotic factors (e.g., weed invasion, herbivory, lack of pollination) or abiotic factors (e.g., changes in hydrology or soil structure and processes). Conceptual models involving a state and transition approach and the recognition of potential thresholds (6, 25) (**Figure 1**) are increasingly used to understand nonlinear and nonequilibrium ecosystem dynamics (39, 42, 43). However, there is ongoing debate about when and where alternative stable states might be expected to occur (44–48).

Deciding when and where such models may be considered appropriate in a restoration context is currently a key task (49, 50). There are no clear generally applicable methods for recognizing where thresholds are likely to be important. Proposed methods of identifying thresholds and the existence of alternative stable states [e.g., (43)] are highly intensive and dependent on detailed experimentation and observation, which may be beyond the scope of most restoration projects. Relatively few studies have directly examined whether persistent degraded states are actually alternative stable states or not. However, the persistence of undesirable states, such as those dominated by aggressive nonnative plant species, indicates that the system may be stuck and will require management intervention to move it to a more desirable state (38, 51).

In some cases, decisions on what needs to be done might be relatively straightforward and can be based on sound scientific data and adequate knowledge of the system. However, in other cases, the decisions may be more complex, involving the use of incomplete knowledge and conflicting viewpoints.

TYPES OF INTERVENTION

Restoration activities span a spectrum of degrees of intervention, ranging from virtually none to the complete construction of novel ecosystems (**Figure 2**).

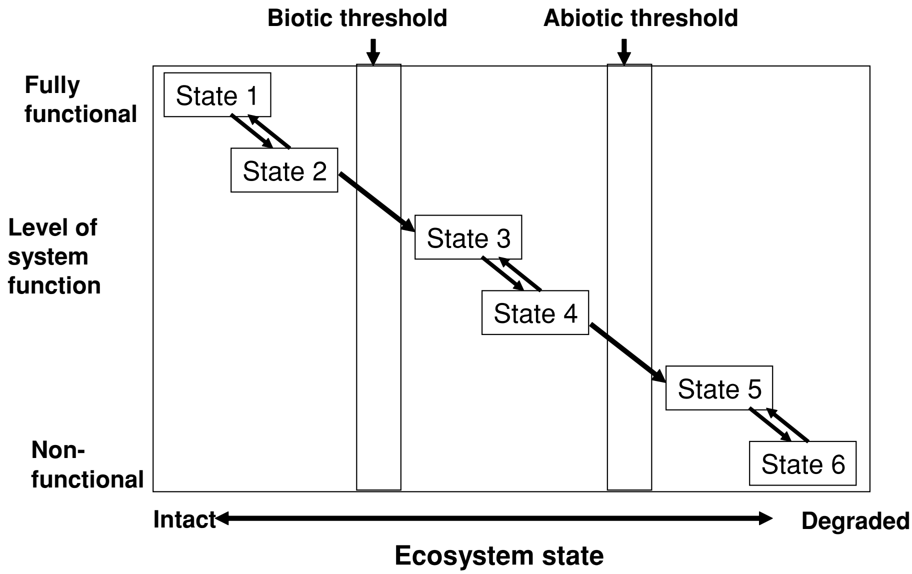

Figure 1

Summary of the state and transition approach to ecosystem degradation and restoration. States are indicated in boxes, and possible transitions between states are shown by arrows. Hypothesized thresholds, which prevent transition from a more degraded state to a less degraded state, are indicated by the vertical shaded bars: Such transitions can either be biotic (for instance, competition or grazing) or abiotic (for instance, changed physical or chemical conditions) (114).

No Intervention

A default decision is to do nothing and "let nature take its course." This approach may be considered the most appropriate in, for instance, wilderness management where the underlying aim is to prevent or minimize human intervention (52, 53). It may also be considered appropriate when a degraded system appears to have

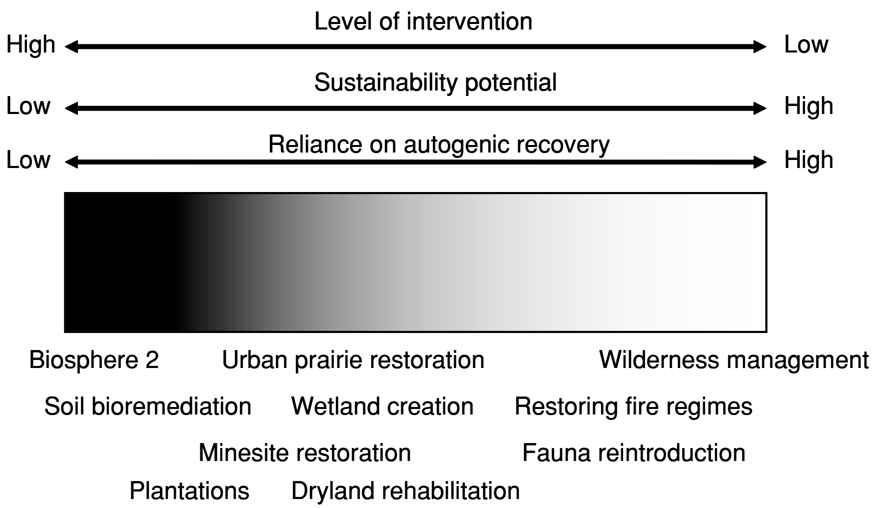

Figure 2

Representative restoration activities across a spectrum of levels of intervention. Modified from (9, 150).

the capacity to recover unaided: Capitalizing on the inherent resilience of the system may be the most effective and cost-efficient way of restoring the system (54). For instance, recent studies from Europe suggest that allowing spontaneous succession to occur may be the most ecologically appropriate and cost-effective way of restoring gravel and sand pits (55). Allowing spontaneous succession is most likely to be an effective restoration approach mainly in areas where neither environmental stress nor productivity is particularly high (56) (**Figure 3**). A key message from this is that a preliminary assessment of the capacity for the ecosystem to recover unaided is essential so that time and resources are not wasted on potentially expensive restoration actions, which may or may not result in better outcomes.

Unfortunately, a "do nothing" approach often applies for other reasons, including lack of management resources or the inability of stakeholders to agree on a suitable course of action. In these cases, the outcomes can be unpredictable and potentially undesirable. Even in wilderness management, increasingly difficult decisions have to be made about whether to intervene to control invasive species, modify fire regimes, etc. (52, 53).

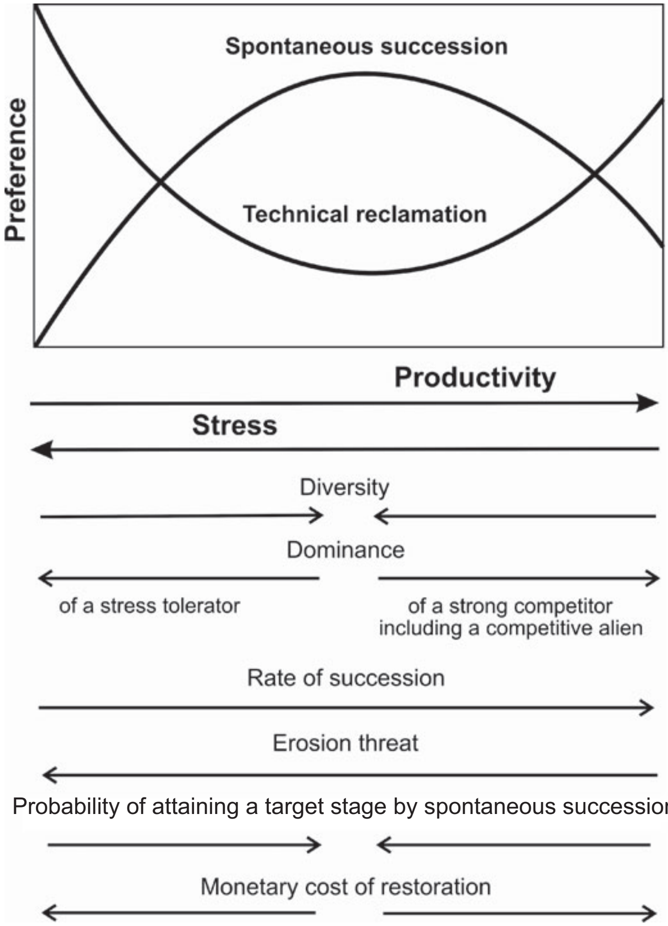

Figure 3

Relative preference of spontaneous succession and technical reclamation along the productivity-stress gradient. Characteristics relevant to restoration are also related to the gradient (56).

Abiotic Interventions

At their simplest, abiotic interventions aim to change the physical or chemical environment and then revert to a let nature take its course approach. This is particularly the case where a clear abiotic threshold has been identified that is preventing system recovery. Restoring water flow into the Mesopotamian Marshes is an example of this approach (22). However, in practice, further biotic interventions are used to guide or alter the ecosystem's biotic development (see below).

Alteration of the physical or chemical environment underlies many restoration efforts, including those that seek to restore surface heterogeneity in drylands to reinstate local control of water and nutrient flows (23, 25) and those that seek to reinstate meanders, riffle-pool sequences, and other structures in rivers (57, 58), or to remove barriers to stream or river flow such as dams (59). Both of these approaches are being used in attempts to restore rivers and water flows in southern Florida (26, 27).

Wetland creation also basically entails providing the physical structure for water retention and ensuring that the physical and chemical conditions are suitable for biotic colonization, although this is sometimes followed up with active vegetation reestablishment (60). Similarly, mine site rehabilitation frequently has to reinstate soil structure and ameliorate soil chemistry prior to the reintroduction of biota; however, this process is often followed up with active reintroduction of plants via seeding and planting. An example of this approach can be found in the restoration of surface-mined lands in the *Eucalyptus marginata* forests of southwestern Australia (61).

Fire is an important element of many ecosystems and represents an abiotic process whose characteristics often depend heavily on the biotic structure of the system. Fire intensity and spread depend partially on the types and configuration of fuel available, and this in turn is determined by the spatial distribution, age, and health of component plant species (62, 63). Fire-prone ecosystems generally have characteristic fire regimes determined either by the incidence of lightning ignitions or by human fire use, particularly by indigenous peoples (64, 65). Alteration of historic fire regimes is a frequent cause of current management headaches. Fire suppression in many ecosystems has resulted in catastrophic wildfires or the loss of particular ecosystem types as a result of increasing fuel loads and growth of woody species (28, 29). Alternatively, too frequent fires, for instance, caused by arson or accidental fire in areas adjacent to cities, can lead to the conversion of woody ecosystems to herbaceous dominance (66). Restoration in both of these cases involves attempting to reinstate a fire regime more closely approximating the historic regime, either by controlling ignition sources where possible or by manipulating vegetation structure and hence altering fuel loads and distributions.

The key message from the array of abiotic interventions that are being applied in various restoration settings is that it is essential to assess whether there are abiotic factors preventing system recovery. If there are, in some cases, simply addressing these factors may be all that is needed to set the system on a trajectory of recovery. These may range from local actions to large-scale regional alterations of hydrological or disturbance regimes. In other cases, further interventions involving the living components of the systems may be needed.

Biotic Interventions

Biotic interventions generally entail the reinstatement of species or suites of species considered desirable in the restored ecosystem. Often, the focus is initially on the plant community or on individual plant species, e.g., restoring the dominant plant species and/or representative species from the desired community type. Methods for doing this vary depending on the degree of degradation and the expected successional dynamics. Where the restoration starts with a bare substrate, the intervention depends on the expected successional dynamics. In locations where it is possible to assume that a succession will proceed from a pioneer stage on to later stages, then it is possible to initiate the process and then let the process proceed. In some cases, such as the restoration of abandoned pastures in tropical areas, provision of some early structural elements can provide perches to act as foci for dispersal of seeds by birds (67). By contrast, where an "initial floristics" model of succession operates (in which species from throughout the successional sequence establish early and replace each other on the basis of differential longevities), then it is important to ensure that later successional species are introduced at the time of initial restoration (68). In other situations where systems are stuck for some reason, desired species may need to be reintroduced (38).

In some cases, the focus of restoration is on particular plant species, often dominant structural species, such as in measures to encourage regeneration of tree species, leading to the development of woodland or forest ecosystems. For instance, measures including reducing grazing pressure from deer and other herbivores and minimizing fire occurrence are leading to successful regeneration of *Pinus sylvestris* in areas long devoid of woodland in Scotland (21). In other cases, the focus may be on rare and threatened species. In such cases, an array of techniques is available, including seed storage, tissue culture, germination enhancement, and translocation (69). Genetic factors relating to seed provenance need to be considered when sourcing seed for restoration efforts, although there is ongoing debate as to the desirability and feasibility of attempting to define and use local provenance material (70, 71), particularly in the context of rapidly changing environments, as discussed below. Providing a suitable habitat for reintroduced plants is also important, and continued survival of introduced material will depend on favorable environmental conditions.

A particularly important biotic intervention relates to the grazing regime experienced by the ecosystem. In many different systems, degradation results from overgrazing either by livestock or elevated populations of native herbivores. For instance, arid lands, which have been overgrazed, lose their vegetation cover, leading to poor water and nutrient retention and resulting erosion, and elevated numbers of ungulates can prevent tree regeneration in woodland and forest systems (21, 72). However, cessation of traditional grazing practices can lead to unwanted ecosystem changes, such as reestablishment of forest vegetation in seminatural grassland systems; hence, restoring the system requires putting grazing animals back (73). Using livestock as restoration agents can also be a novel and sometimes controversial approach elsewhere, particularly where the prevailing conservation paradigm is that livestock grazing is detrimental to the ecosystem. An example of such an approach is the use of cattle to reduce the impacts of nonnative grass invasion into grassland on serpentine soils in California (74).

Reintroduction of fauna is a common focus of restoration projects. Fauna species which have become rare or locally extinct (because, for instance, of past hunting or high levels of predation) may be the subject of recovery and reintroduction programs. Recent high-profile examples include the reintroduction of wolves to the Yellowstone area in the Rocky Mountains (75) and the recovery of the California condor (76). Reestablishment or reintroduction of fauna that are keystone species or ecosystem engineers (77) may lead to dramatic ecosystem changes and can be the most effective way to encourage ecosystem restoration. For instance, the reestablishment of beavers in North America and Europe led to reinstatement of lost stream channel characteristics (78) and the reintroduction of wolves in the Rocky Mountains in the United States led to tree regeneration through their impact on herbivore numbers and behavior (79).

An extreme form of fauna restoration calls for the introduction of African megafauna, such as elephants into North America, on the basis that similar megafauna were present in the distant past but were driven extinct by humans (80, 81). These proposals suggest returning to a prehuman condition and contend that North American systems were adapted to such fauna and are now missing components with likely important functional significance. Although an interesting academic thought piece, it is difficult to see how this proposal could be taken seriously, given the known potential for nonnative species to have dramatic and often unwanted impacts on the ecosystems they invade, and given that the ecosystems have had several thousand years without the influence of these megafauna species.

Often it is assumed that if you put vegetation back the fauna will follow, and this is a common assumption in restoration, especially in revegetation, habitat restoration, or mine site restoration (82, 83). This suggests an underlying assumption of bottom-up control of overall community structure, compared with the top-down approaches of reintroduction or control of predators and herbivores discussed above. However, it is clear that fauna can also play important roles in plant dispersal and reintroduction to restored areas and that providing perches, which encourage mobile fauna species to visit restoration sites, can significantly speed up colonization processes (84–86).

The converse of encouraging particularly desirable species to recolonize is the need to control invasive species that alter ecosystem structure and function or prevent ecosystem recovery. Nonnative plant species are prevalent in many ecosystems, and often, restoration interventions are focused almost entirely on weed removal and control (87, 88). Similarly, many fauna restoration projects have feral predator control or exclusion as a key component. For instance, significant success in increasing or restoring native fauna populations has been achieved in Australia and New Zealand following the effective control or exclusion of feral predators, such as foxes or mustelids (89–91). However, nonnative species are an increasingly common component in many systems (92, 93), and it will not be possible to control or eradicate all of these species, especially in the case of plants. Thus, there is a need for an integrated approach, which focuses on prevention of further invasion, early eradication, and control of existing problems (94). Also, there is increasing recognition that not all nonnative species have deleterious effects, that nonnative species can sometimes perform important roles in restoration and conservation, and that removal of individual species needs to be placed in a broader ecosystem context (88, 95). Also, public perception is often mixed on whether particular nonnative species are necessarily a problem, for instance, in the case of nonnative trees in urban parks (96, 97).

The key message regarding biotic interventions is that biotic interactions are invariably complex, and careful attention to the likely impact of interventions on the overall biotic community is required. Sometimes the intervention needed is obvious, for instance, in the case of the removal of a highly invasive nonnative plant species. In other cases, the required intervention may be less obvious or counterintuitive. In all cases, nothing beats a good detailed understanding of the local ecosystem.

Broader-Scale Interventions

As well as the varied types of local interventions discussed so far, there is a suite of broader-scale interventions that aim to restore patterns and processes at the landscape or regional scale. Such activities may be aimed at restoring landscape flows by increasing connectivity or through hydrological management (27, 98) or at reinstating regional landscape structures and functions. For instance, restoration of barrier islands on the Louisiana coast is seen as an essential element in a strategy to limit future damage from hurricanes (99). Usually, these broad-scale efforts require the development and implementation of regional plans involving multiple local actions of the types discussed previously.

ONE-OFF OR ONGOING INTERVENTIONS?

A common assumption is that the aim of restoration is to fix the problem and move on. If done properly, restoration would repair the system and allow the continuation or reestablishment of essential population and ecosystem processes so that the system would become self-sustaining (8). Many restoration projects have a goal of doing a one-off intervention and then leaving the system to sort itself out thereafter: examples include one-off weed removal or soil amendment treatments or the construction of barrier structures in arid lands. Although this goal may be appropriate in some cases, it is unrealistic, and perhaps undesirable, in others. In many cases, for instance, the need for weed management is ongoing, particularly in highly modified environments such as urban areas. Similarly, fire regime management requires repeated applications of particular types and sizes of fire or, conversely, the prevention of particularly destructive wildfires. Hence, it is likely that, in many cases, restoration in fact needs ongoing management.

Additionally, many ecosystems were, in fact, maintained by human activity in the past and have fallen into disrepair because of the cessation of these activities. There is increasing evidence that humans have had a much more pervasive influence on ecosystems around the world than previously thought (100–102). In many cases, indigenous people were ecological keystone species, exerting a strong influence on the environments they inhabited (100, 103). The intensive management applied, for instance, to the prairie and oak savannah remnants in the Chicago region recognized the importance of Native American management, predominantly by using fire, and there are efforts to reinstate it (16, 17, 104). In such cases, the ongoing success of the restoration effort may, in fact, depend on continuing management. This is doubly so if there are persistent, problematic weedy species to deal with. Therefore, ongoing involvement of volunteers who devote their time to carrying out the necessary management is likely to be valuable, if not essential. The type of intense community engagement advocated by Jordan (11) and Higgs (14) may allow the reestablishment and retention of historic or authentic ecosystems, even in the face of ongoing environmental change. Although such ecosystems may be viewed as "living museums" if there is sufficient citizen support and enthusiasm to maintain these ecosystems, then they may be viewed as valid restoration outcomes. If this requirement for ongoing intensive management is recognized, then the objective of the restoration is not necessarily to apply a one-off fix-it solution but to engender an ongoing intimate interconnection between humans and the ecosystem.

SETTING PRIORITIES

Given the array of potential interventions, how do we decide what to do, and in which order? The process of ecosystem restoration can be viewed as an attempt to move a given area from a degraded state of relatively low quality toward a target of improved condition (82) (**Figure 4**). Assessment of the current condition relative to the target is followed by consideration of which intervention options are likely to improve the situation. The question of how this is measured is, of course, a key concern; this could, for instance, be related to the habitat requirements of particular species of concern, or the presence of key plant species, altered fire frequency, or a variety of composite measures of ecosystem integrity or health (105). How to measure

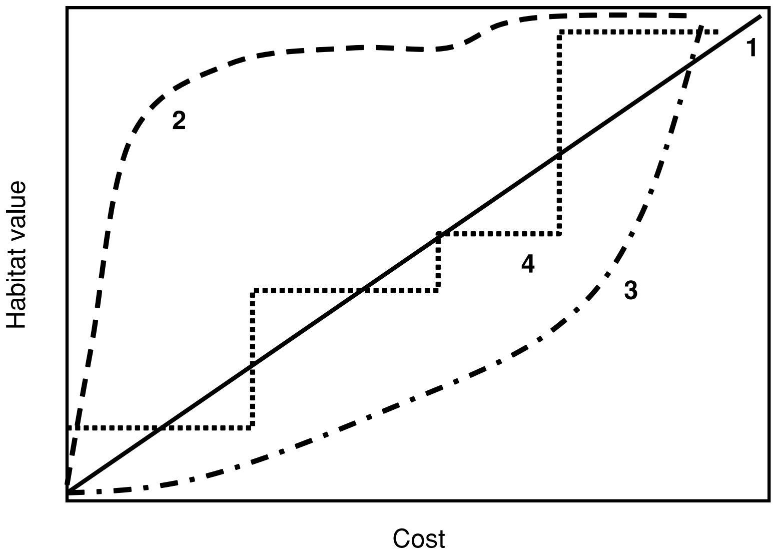

Figure 4

Value of restored habitat versus the financial input to the restoration project for a number of different scenarios. 1. Habitat value increases linearly with the amount spent on the restoration. 2. Restoring a high proportion of the desired habitat value is achieved relatively cheaply, but achieving further small additions to habitat value becomes increasingly expensive. 3. Relatively little value is restored until considerable expenditure is invested. 4. Habitat value increases in a step-wise way in response to the need for expenditure to overcome particular biotic or abiotic thresholds (82).

restoration success is of key importance in setting goals and assessing progress toward them, and yet this is done in many different ways and with a varying degree of effectiveness (106). Conversely, the success or otherwise of restoration projects needs to be assessed in relation to the goals set for the project, and setting unrealistic goals inevitably leads to lack of success (107).

Clearly, we will not always have a good understanding of the precise relationship between particular management actions and the degree of increase in habitat quality or ecosystem condition. However, thinking about things in this way at least provides a logical method for sorting out what might be useful to do. In addition, cost factors may render some actions unrealistic or unachievable under current conditions. In the case where essential actions are unachievable, then it is probably best either to consider an alternative set of goals for the restoration, or not to embark on the restoration effort at present, recognizing that circumstances may change and technological or other advances may render the action more achievable in the future.

Hence, we need to be clear about (*a*) what our goals are for restoration and (*b*) what the options are for achieving these goals. The goals will determine the level and extent of intervention required, and the options available will determine the likelihood of achieving the agreed goals. Obviously, there is no point in setting goals that are ultimately unachievable. Goals need to be set at national, regional, and local levels, and within broadly stated goals, there will be subgoals relating to particular landscapes or ecosystems. In order to set and achieve these subgoals, we need a clear assessment of the value of particular ecosystems/landscapes, the degree of threat, and the likelihood of successful management intervention. This then allows an assessment of the likely level and type of management intervention necessary. It is important to consider the suite of alternative interventions available and their relative costs and benefits.

In particular, it is important to emphasize that, while we are focusing our discussion on restoration, the most cost-effective option is usually to avoid ecosystem damage in the first place. Hence, preventative measures should always be considered first, and the availability of a restoration option should not be used as an excuse for ongoing damage or destruction of ecosystems. This is particularly important where offset or mitigation options are considered under "no net loss" arrangements, which have the underlying and often fallacious assumption that an existing ecosystem can be destroyed and replaced with a constructed system elsewhere (108).

Another important element is the consideration that not all ecosystems and landscapes are equal in value, degree of threat, or responsiveness to management treatment. Some ecosystems and landscapes may already be beyond the point where social resources and current technologies can reverse the processes of degradation underway. We need to acknowledge this and decide on rational and effective approaches to the issue. This is particularly important when ongoing rapid environmental change is factored in, as discussed below.

RESTORATION ECOLOGY IN A RAPIDLY CHANGING WORLD

It is becoming increasingly apparent that the theoretical and practical underpinnings of restoration have to be reconsidered in the light of rapid environmental changes, which can act synergistically to transform ecosystems and render the likelihood of returning to past states more unlikely. We are currently in a period of rapid, anthropogenic-driven climate change without historic precedent. This rapid climate change is in addition to the widespread ecosystem changes brought about by land-cover change, fragmentation, invasive species, altered disturbance regimes, and pollution (109). Resulting ecosystem changes are leading to the formation of "novel ecosystems," systems whose composition and/or function differ from any historical system (92, 93), and the increasing likelihood of a no-analogue future, one in which we have no historical reference point to refer to (110). Management of intact ecosystems and restoration of degraded ecosystems are seen as critical to the protection of both biodiversity and ecosystem services in this period of strong human alteration of ecosystems. Considerable effort and resources are being expended worldwide on ecosystem management and restoration, and yet there has been little serious thought given to how to do this in the context of a no-analogue future. Assessing the ecological consequences of climate change and interacting factors, and how they might be mitigated, has recently been called a "Grand Challenge" in ecology (111).

This has led to increasing calls for a new approach in which ecological restoration focuses on the future as much as, if not more than, on the past (112–114). This focus can ideally lead to restoration being both a reactive response to rapid environmental change and part of a proactive strategy, which identifies opportunities for deriving future benefit and preventing further problems in the future. However, the pathway toward this new formulation is not yet clear and requires new ways of thinking and clearer insights regarding the dynamics of ecosystems under novel conditions.

A series of interrelated factors needs to be considered in this regard (**Figure 5**). First, there is a set of interacting global change drivers, which are sometimes likely to act synergistically and result in a set of ecosystem responses, driven by the inherent ecosystem dynamics and resilience, and how those are affected by the various drivers. The outcome of these dynamics is likely to include the development of novel no-analogue ecosystems. Then, there are likely to be a variety of social responses to these ecosystem changes, and these responses will feed into the set of management actions that are feasible and desirable to undertake. As depicted in **Figure 5**, these sets of factors can all affect

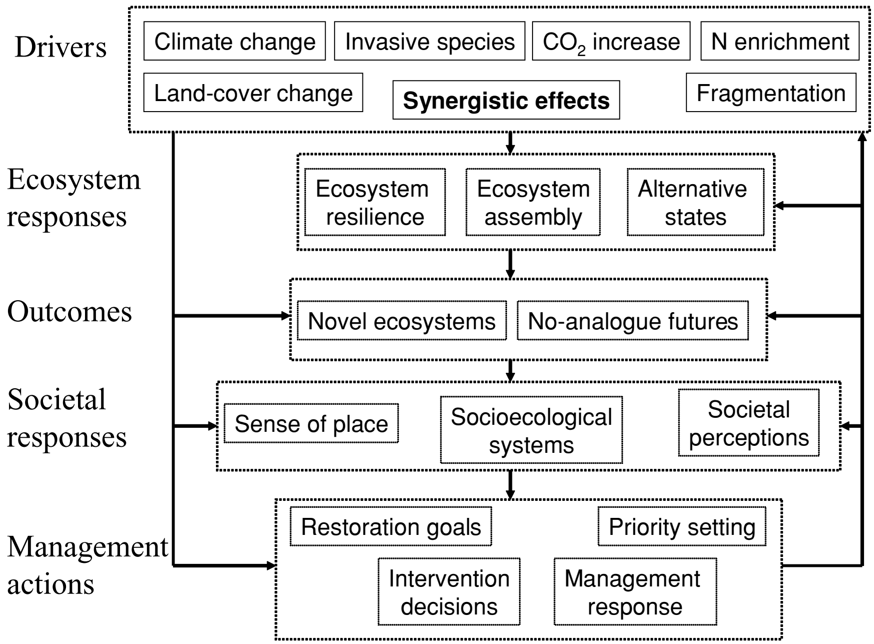

Figure 5

Interactions among global change drivers, ecosystem and societal responses, potential outcomes, and management actions (note: diagram illustrates indicative factors and is not meant to provide a comprehensive overview).

each other, leading to a complex set of interrelations; yet, the figure only includes representative elements in each set and does not include the ultimate drivers of change such as global trade, human population needs, and others. The figure could also be validly reformulated so that the socioecological systems encompassed everything else. The key point remains the same however, i.e., that there is a highly interrelated series of factors to be considered when considering restoration activities in the context of rapid environmental change. There are three key sets of interrelated questions that need to be addressed relating to ecosystem restoration and management in a rapidly changing world:

1. How do climate change, invasive species and other potentially synergistic drivers act and interact to alter the dynamics of ecosystems and the potential outcomes of restoration? Climate change has become an increasing focus of attention in recent times as scientific consensus is reached concerning both its occurrence and its causes, but it has only recently been considered in the context of restoration (113). It is increasingly recognized that impacts of a changing climate are already apparent in responses of species range shifts or contractions, changes in phenology, and disruption of species interactions (115, 116). Increasing efforts are being made worldwide to develop a greater predictive capacity in relation to likely changes in regional climate and their impacts on species and ecosystems. Although climate models are improving, it is generally accepted that the level of certainty provided by their outputs remains low at the regional scale. The main approach taken to determining biotic response to climate change has been the use of bioclimatic envelopes, which correlate current distributions with current climate parameters and predict future distributions from climate change scenarios. While providing some initial guidance as to the potential need to facilitate species movement to track climatic suitability, such correlative models are recognized as providing only a partial picture of potential biotic response (117, 118). More mechanistic approaches are being developed, but models still rarely consider either species interactions or the potentially synergistic impacts of changing climate with other change drivers, such as land-cover change or invasive species (119, 120). Experimental studies have indicated that species' responses sometimes, but not always, vary depending on whether single or multiple factors are considered and whether species are examined individually or in combination with other species (121, 122). In addition, responses can change over time, with recent experiments indicating complex interactions and temporal trends [e.g., (123, 124)].

We are thus faced with multiple layers of uncertainty concerning how species and ecosystems are likely to respond to climate change combined with other drivers. Recently, a multipronged research approach has been advocated involving modeling, broad-scale observations, and small-scale studies informed by large-scale patterns to refine causal mechanisms (125). The implications of climate change for both understanding past and present ecosystems and designing effective restoration interventions have been relatively little explored (113, 126).

2. If global change drivers result in novel ecosystems without past analogues, how should such systems be managed, and how will the departure from historic ecosystems affect public perceptions and participation in conservation and restoration activities? It is becoming increasingly apparent that in response to rapid environmental change, including climate and land-use change and biological invasions, novel ecosystems with new species combinations and functional characteristics are emerging (92, 93). Multiple and interacting factors lead to threat syndromes with potentially great impacts on species and ecosystems (127), and ecosystem change may be quite sudden, with rapid transitions from one state or type to another (128). Relatively little thought has been given to the likely implications of these new assemblages, both from an ecological perspective and in terms of their societal impacts. At present, regional programs for natural resource management rely heavily on the involvement of local communities to conserve and restore lands outside of public reserve systems. However, it is likely that radically different approaches to conservation, restoration, and resource management may be necessary and that these approaches may have profound societal impacts relating to changes in how society perceives and values the natural environment. What are the consequences of changing biotic assemblages for conservation and restoration goals and practices and for local community perceptions of nature, landscape preferences, and sense of place (129)? Maintaining the status quo or restoring systems to past states may no longer be options, and discussions relating to native versus nonnative species and local versus nonlocal provenances may need to be revisited (113, 130).

A key question for landscape management in the future is how to balance the ecological and human values of past ecosystems with the need to (*a*) recognize and understand the role of novel ecosystems under conditions of rapid environmental change and to (*b*) incorporate the values of both past and novel ecosystems to build resilient ecosystems for the future. A second key question involves the role of people in the management of natural ecosystems, as the traditional distinction between production and conservation activities softens in landscapes where the provision of natural capital (e.g., regulation of ecosystem processes, provision of habitat, carbon capture, and food and fiber production) is the primary objective of integrated conservation, restoration, and natural resource management (131, 132). This may require a fresh approach to how we perform scientific research in this arena, changing the focus to what has been called "a more public ecology," which is more contextual, integrative, and accessible (133) and takes greater cognizance of socioeconomic aspects (134).

3. What practical guidance can be given to managers, policy makers, and the public to allow sensible decision making related to the protection of biodiversity and maintenance of ecosystem services in the face of an uncertain future? There is considerable work underway currently on how to make better decisions in conservation and resource management using decision support tools and systematic conservation planning methods (135, 136). However, in order to make sensible decisions, there have to be clear options available to decide among. Although there has been much discussion of the likely impacts of climate change on ecosystems and the potential for synergistic effects with other drivers is recognized, there has been little serious thought given to actual management responses to these, apart from broad generalizations. A broadly based literature review (137) recently suggested, "First, strong consensus exists across two decades and a wide range of literature in what scientists assert needs to be done to manage for climate change. Second, many consistent recommendations are nevertheless vaguely defined and unclear as to how they can be implemented. Third, most of the suggested actions will require far greater coordination and integration of research scientists, restorationists, land managers, and policymakers than currently exists." Certainly, a comparison of two edited volumes dealing with climate change and biodiversity, one published in 1992 and the other in 2005 (138, 139), shows considerable advance in our understanding of the likely consequences of climate change but remarkably little advance in terms of critical thinking on the options available for responding to these consequences. The options being discussed currently are remarkably similar to those put forward in 1992 (140) and involve activities such as maintaining or improving landscape connectivity (141) and the facilitated movement of organisms (130).

We thus currently have a situation where our capacity to make decisions on a more rational and effective basis is improving, but we have not yet clarified what management options are likely to be either desirable or feasible in terms of responding to global climate change in concert with other key drivers. There is clear recognition of the problem, but no obvious way of dealing with it in a practical sense. How then can we ensure that biodiversity persists and ecosystem services are maintained in the face of rapid, widespread, and uncertain ecological change? The key challenge will be to decide where, when, and how to intervene in physical and biological processes to conserve and maintain what we value in these places. To make such decisions, planners and managers must consider goals, what is valued, and what needs to be sustained. Where interventions are needed, what outcomes are desired, and how will society respond to such interventions and outcomes? These difficult questions need to be answered in the context of a system in which it is already often difficult to bridge the gap between science and policy (142) and in which the majority of the public remains only marginally engaged in concern for the environment.

CONCLUSIONS

For much of the twentieth century, the science of ecology and the practice of managing ecosystems aimed at developing more certainty about how systems worked and what the outcomes of management interventions would be. If we were to caricature the prevailing paradigm, we could say that there was a general belief in the balance of nature and relatively stable environments (143), in the idea that pristine nature existed in areas untouched by humans (144, 145), and in what the goals for conservation management should be, i.e., minimize or take away human impacts on nature, and it will recover and basically look after itself.

Now, however, as the twenty-first century unfolds, it appears as if all posts on which to hitch the sought-for certainty have been knocked away. We are faced with the prospect that ecological systems are more complex and less easy to understand and predict than we thought. The idea of the balance of nature has been replaced with the flux of nature (146–149), and ecosystems are thought to be mostly in nonequilibrium, and their dynamics are not only complex but also dependent on the spatial context and the history of natural disturbance and human influence. Increased understanding of the pervasive influence of indigenous humans on ecosystems around the world (100–102) and the likelihood that indigenous people were ecological keystone species exerting a strong influence on many environments (100, 103) require a rethink of how we view the past and plan for the future.

All of this has to be coupled with the increasing pace of environmental change being experienced. Increasing rates of change in climate, land use, pollution, and number of invasive organisms are all leading us into uncharted territory, and the future has no analogues from the past that might guide us. This no-analogue future is where we have to try to manage the environment using new approaches from our revised understanding of how nature works.

This suggests that our knowledge and understanding are always likely to be incomplete and are contingent on both the types of knowledge that have been included and on the values in play at the time. For ecological restoration, which is a very mission-oriented problem-solving activity, this can appear very challenging. The goal is, broadly speaking, to fix damaged ecosystems, and there may be a hint of hubris in assuming that we always know (*a*) what the problem is, (*b*) how to fix it, and (*c*) what the end result should be. So restorationists undertake projects ranging from small, local efforts to remove problem weeds from urban nature reserves through to massive regional projects aiming to replumb whole river systems, assuming that they know both what they are doing and what the outcome will be. In general, we are undoubtedly getting better at this, are often simply trying to undo problems created by activities conducted in times of even less understanding, and have learned from past mistakes.

However, it remains important to question the extent to which humanity can meddle with nature, albeit in an increasingly intelligent way, given the legacy of problems from past attempts. Intervening in complex ecosystems, even with good intentions, can often have unexpected consequences, and the likelihood of this happening can only increase in the future as environmental conditions continue to change rapidly. Hence, we are always running a race between, on one hand, what we think we know and understand and, on the other hand, the reality of rapidly changing systems and revised ideas in the light of new insights. The ways in which humanity intervenes may need to change on the basis of our changing understanding of how complex ecosystems work, and adaptive management will need to be effectively used to a much greater extent than is currently the case. The challenge for restoration ecology is to provide both contextual analyses that are relevant in particular situations and more general guidance that is broadly applicable—all of which assist in the endeavor of designing and implementing useful interventions and monitoring their effectiveness in the context of complex, rapidly changing environments.

SUMMARY POINTS

1. Restoration ecology attempts to provide scientific underpinnings to guide management interventions aimed at repairing environmental damage.
2. Restoration activities range from local to regional and from volunteer efforts to large-scale multiagency activities.
3. Interventions vary from a do nothing approach to a variety of abiotic and biotic interventions aimed at speeding up or altering the course of ecosystem recovery and/or overcoming barriers or thresholds preventing such recovery.
4. Revised understanding of ecosystem dynamics, the place of humans in historic ecosystems, and changed environmental settings owing to rapid environmental change all impact on decisions on which interventions are appropriate.
5. Potentially synergistic global change drivers interact to alter the dynamics and restoration of ecosystems.
6. Novel ecosystems without historic analogue are likely to result from global environmental change and species movements.

FUTURE ISSUES

1. How do climate change, invasive species, and other potentially synergistic drivers act and interact to alter the dynamics of ecosystems and the potential outcomes of restoration?
2. If global change drivers result in novel ecosystems without past analogues, how should such systems be managed and/or restored, and how should the restoration goals be determined? What interventions are most appropriate, and when and where should they be applied?
3. How can thresholds in ecosystem dynamics be identified and managed?
4. How will departure from historic ecosystems affect public perceptions and participation in conservation and restoration activities?

5. What practical guidance can be given to managers, policy makers, and the public to allow sensible decision making related to the protection of biodiversity and maintenance of ecosystem services in the face of an uncertain future?

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The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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