Restoration Ecology: Repairing the Earth's Ecosystems in the New Millennium

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Abstract

The extent of human-induced change and damage to Earth's ecosystems renders ecosystem repair an essential part of our future survival strategy, and this demands that restoration ecology provide effective conceptual and practical tools for this task. We argue that restoration ecology has to be an integral component of land management in today's world, and to be broadly applicable, has to have a clearly articulated conceptual basis. This needs to recognize that most ecosystems are dynamic and hence restoration goals cannot be based on static attributes. Setting clear and achievable goals is essential, and these should focus on the desired characteristics for the system in the future, rather than in relation to what these were in the past. Goal setting requires that there is a clear understanding of the restoration options available (and the relative costs of different options). The concept of restoration thresholds suggests that options are determined by the current state of the system in relation to biotic and abiotic thresholds. A further important task is the development of effective and easily measured success criteria. Many parameters could be considered for inclusion in restoration success criteria, but these are often ambiguous or hard to measure. Success criteria need to relate clearly back to specific restoration goals. If restoration ecology is to be successfully practiced as part of humanity's response to continued ecosystem change and degradation, restoration ecologists need to rise to the challenges of meshing science, practice and policy. Restoration ecology is likely to be one of the most important fields of the coming century.

Key words: ecosystem repair, conceptual framework, dynamic ecosystems, restoration goals, thresholds, success criteria.

Introduction

The start of the new millennium is a useful time to reflect and take stock of where we are and where we think we should be going. The latter part of the last millennium saw unprecedented changes in all aspects of human existence on Earth, not the least of which were the increasing numbers of humans on the planet and increasing impacts of humanity on Earth and all its ecosystems. In the twilight of the second millennium we switched to a new relationship with our planet, one in which humanity dominates all other living things, sequesters the majority of the products of photosynthesis and most of the available freshwater, and increasing proportions of Earth's fish stocks for its own use (Vitousek et al. 1997). In addition, humanity is collectively changing the composition of the atmosphere and transforming the Earth's ecosystems at an unprecedented rate, and in the process causing widespread damage to the life-support systems upon which we, and every other living thing, depend.

The new millennium is thus something of a nexus for humanity, at which we need to decide whether we wish to proceed with this huge transformation of our planet, and in so doing, put our continued existence at increasing risk. Or whether we want to seek alternatives in which we aim to protect the resources, both living and abiotic, that we have left, and set about repairing some of the damage we have inflicted in the past. It is our hope that we have the collective wisdom to choose the latter course, and it is in this context that we consider the rapidly developing field of restoration ecology. If we are to persist on our planet, repair of Earth's ecosystems and the services they provide will be an essential component of our survival strategy. How well placed is the science of restoration ecology to meet this challenge? Does it have a sufficiently well-developed conceptual or theoretical base to be applied broadly? Does it have a suitable arsenal of strategies and tactics to tackle the often intractable problems it encounters? Moreover, does it have sufficient pathways into policy and practice to enable it to be applied effectively and quickly?

In this paper we examine these questions, and provide what we hope will provide pointers for the way ahead.

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Restoration as Part of Land Management

Much of the practice of ecological restoration is carried out after the devastation of land has occurred, which is best summed up by the phrase "I wouldn't start from here, if I were you." It is useful to identify where restoration ecology fits in with current practices in land use. An apparent dichotomy is often erected between conservation and restoration, indicating that they are considered to be alternative options. Certainly, where funds are short for natural resource management, priorities have to be decided, and choices made (for instance, between land acquisition for nature reserves and restoration of degraded habitat areas). However, the dichotomy is a false one, since restoration activities should ideally be placed within a broader context of sustainable land use and conservation. In terms of nature conservation, there is no substitute for preserving good quality habitat, and the maintenance and management of this is a number one priority. However, in many parts of the world, this is either no longer an option because few areas of unaltered habitat remain, or it is no longer sufficient since the remaining habitat on its own cannot sustain the biota, and hence needs to be improved or expanded. Hence restoration is an integral part of conservation in many areas, and restoration ecology and conservation biology have much to gain from closer interaction with each other (Young 2000).

Similarly, restoration has an integral part to play in the development and maintenance of sustainable production systems. Virtually nowhere in the world can we claim to have truly sustainable production systems, since all production systems inevitably degrade the natural resources on which they depend, or rely heavily on external subsidies of energy, nutrients and/or water. If we are to develop sustainable systems, we have first to repair the damage that has been done by past and current systems.

We thus argue that ecological restoration is an integral component of land management in today's world. Hence, restoration ecology needs to ensure that it develops and maintains links with other disciplines relating to land management.

Conceptual Base

Why should restoration ecology bother about having a conceptual base to work from? It has been pointed out repeatedly that ecological restoration has been, and continues to be, practiced widely without apparent recourse to any background conceptual framework (Allen et al. 1997; Palmer et al. 1997). It has recently been suggested that, while we might need to develop conceptual bases to satisfy our academic need for basic research, we shouldn't let this get in the way of the huge operational restoration tasks which are required (Young 2000).

On the other hand, practitioners have identified the need for a much firmer ecological foundation for developing and implementing restoration projects (Clewell & Rieger 1997). In addition, it is becoming increasingly apparent that the assumptions underlying many restoration projects have their roots in outdated concepts of how ecological systems function. This has led to much angst over questions which are now largely irrelevant or unanswerable (Pickett & Parker 1994; Wyant et al. 1995; Parker & Pickett 1997; Middleton 1999). This is particularly true in relation to assumptions on the stability of ecological systems and their ability to return to particular equilibrium states following disturbance (Hobbs & Morton 1999) If we are to train restoration ecologists effectively for the future and equip them with skills that are transportable from one system to another, we need to have an up-to-date and comprehensive conceptual framework to provide a context for their activities.

It seems apparent then, that some attention needs to be paid to the conceptual basis for restoration, but that this be related back to features that are of importance in the practical realm (Fig. 1). As has been discussed more widely concerning the relationship between theoretical and applied ecology (Lawton 1996), there needs to be an ongoing dialog between the conceptual and on-ground aspects of restoration ecology. The conceptual framework aims to provide general understanding of how ecosystems work and the factors involved in system restoration, while on-the-ground application requires methodologies which can be applied in specific situations. Ideally, there should be ongoing interaction between the general and the specific, so that the conceptual basis guides specific actions, while on-the-ground

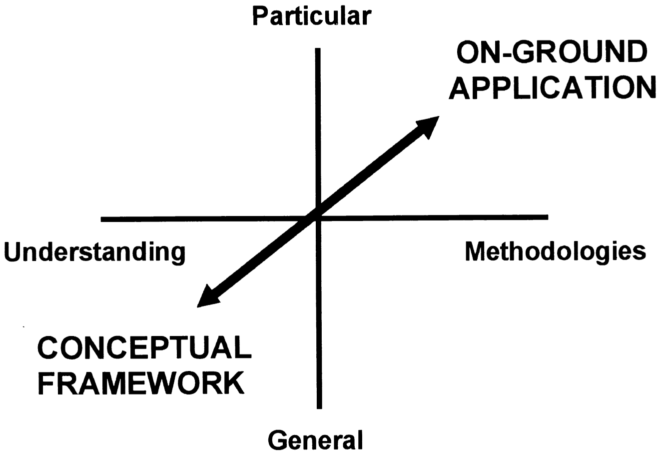

Figure 1. The relationship between a conceptual framework, which aims to provide general understanding of how systems operate, and on-the-ground application, which requires methodologies relating to particular sites and situations. The arrow indicates the need for strong interaction and feedback between the two (adapted from Lawton 1996).

experiences feed back to refine the overall conceptual framework (Hobbs & Yates 1997).

We have both been involved with the development of the conceptual basis of restoration ecology (Harris & Birch 1992; Harris et al. 1996; Hobbs & Norton 1996; Hobbs 1999), as have many others recently (Aronson et al. 1993*a*, 1993*b*; Allen et al. 1997; Pfadenhauer & Grootjans 1999; Urbanska et al. 1997; Whisenant 1999), and we will not reiterate much of this material here. Instead, we will highlight a few key points, which seem to be emerging as central components of this conceptual framework. We will not also dwell on the definition of restoration, since this has been aired repeatedly in the recent literature. While some argue that preciseness of definition is essential (Aronson & Le Floc'h 1996*a*; Higgs 1997), we take the view that goal definition is more important than definition of terms. Whatever a particular activity is called (restoration, rehabilitation, repair or other re- words), the clear enunciation of goals is essential for its success, and the ability to assess the progress toward success.

Dynamic Systems and Restoration Goals

Numerous attributes can be considered when we aim to set restoration goals. For instance, Hobbs & Norton (1996) identified ecosystem composition, structure, function, heterogeneity and resilience as attributes which might be considered. Higgs (1997) similarly suggested that restoration goals should focus on "ecological fidelity," which comprises three elements; namely, structural/compositional replication, functional success and durability. In addition, recent discussions of ecosystem health have put forward system vigor, organization and resilience as properties which can be assessed (Rapport et al. 1998), and hence could be used to develop goals for restoration projects. These are all fine in general terms, but how do we turn these into effective goals for specific projects? Which attributes should we concentrate on? Do we aim for the whole lot, or are some more appropriate than others depending on the circumstances? We suggest that we need a clear rationale for setting goals, which takes into account the nature of the systems being restored, the factors leading to degradation and the types of action required to achieve restoration of different attributes.

Ecosystems are naturally dynamic entities, and hence the setting of restoration goals in terms of static compositional or structural attributes is problematic. Much of restoration ecology is backward looking, seeking to recreate ecosystems with properties which were characteristic of the system at some time in the past. There has been increasing debate as to whether this is either desirable or possible, due to the dynamic nature of ecosystems, and the irreversibility of some system changes (Pickett & Parker 1994; Aronson et al. 1995). Often, past system composition or structure are unknown or partially known, and past data provide only snapshots of system parameters. An alternative is to use nearby existing systems as a model or reference; this certainly can be used to advantage in inferring the likely management interventions needed to restore degraded systems (Yates et al. 1994; Noss 1996). Current undegraded systems at least have the advantage that their structure and dynamics can be studied in detail. These can, therefore, act as potential reference systems against which the success of restoration efforts in degraded systems can be measured. This approach is also not without problems, however, since apparent matching of the restored system with the reference system in terms of composition may mask continued underlying differences in function (Zedler 1995, 1996).

An alternative approach is to explicitly recognize the dynamic nature of ecosystems, and to accept that there is a range of potential short- and long-term outcomes of restoration projects. The aim should be to have a transparent and defensible method of setting goals for restoration which focus on the desired characteristics for the system *in the future*, rather than in relation to what these were in the past (Pfadenhauer & Grootjans 1999). As Captain Kirk on the USS Enterprise said, "What binds us to the past prevents us from embracing the future." If we change the focus of restoration from trying to recreate something from the past to trying to repair damage and creating systems which fulfill sensible goals, we will go a long way to solving many of the conundrums facing the science and practice of restoration ecology. Of course, the goals set for a particular area might still include the retention or restoration of particular compositional or structural elements, but this should be only one of a number of potential goals. Where it is impossible or extremely expensive to restore composition and structure, alternative goals are appropriate. These may aim to repair damage to ecological function or ecosystem services (which may be a more appropriate goal in some situations, in any case – see below), or to create a novel system using species not native to the region or suited to particular physico-chemical constraints (Wheeler et al 1995). These novel systems will be appropriate in some situations and not in others, depending on the pre-defined goals of the restoration activities.

Goal setting thus becomes an extremely important component of the restoration process. Goals for a particular site, or more broadly for a landscape, will need to be determined iteratively by considering the ecological potential for restoration and matching this against societal desires. Higgs (1997) has suggested that "Good ecological restoration entails negotiating the best possible outcome for a specific site based on ecological knowledge and the diverse perspectives of interested stakeholders: to this end it is as much process as product oriented." This argues for an adaptive approach to restoration (Fig. 2), which garners ecological knowledge from as many sources as possible (including on-the-ground practitioners), and uses this knowledge to develop ecological response models which can indicate the likely outcomes of restoration activities. Which restoration option is taken up is decided on the basis of stakeholder expectations and goals, and the extent to which it is implemented depends on the degree of financial and resource input from various sectors, including individual investment and public subsidy or incentives (Hobbs & Saunders 2001). As Higgs (1997) points out, the success of restoration depends greatly on an open and effective process of arriving at mutually-agreed upon restoration goals.

Restoration Options

Arriving at clear restoration goals requires that there is a clear picture of the restoration options available for a particular site, landscape or region. Often, restoration projects launch full steam ahead into activities which may either be inappropriate to particular goals or which target apparent symptoms without considering underlying causes. For instance, in the Western Australian wheatbelt, fencing out livestock is frequently seen to be a primary activity needed for the restoration of native woodland communities, but this fails to address more fundamental changes caused by soil degradation (Yates et al. 2000). Similarly, projects that aim at system restoration through the removal or control of invasive weed species frequently miss the point that the weed invasion is merely a symptom of more fundamental system change (Hobbs & Humphries 1995). Hence, restoration activities need to be prefaced by a rigorous assessment of the current state of the particular system or landscape, and the underlying factors leading to that state. Once this has been achieved, a clearer picture of the necessary restoration activities is possible, and a range of restoration options can be arrived at.

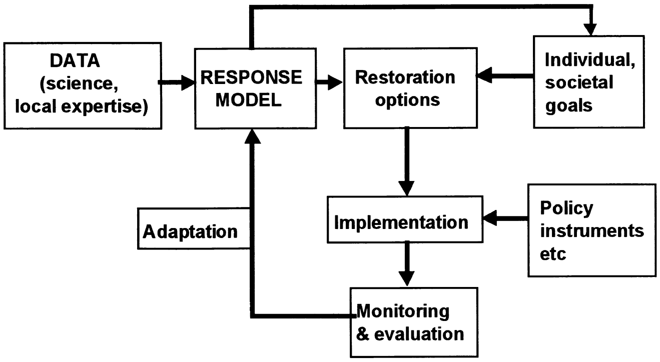

Figure 2. A framework for identifying restoration options based on response models developed from a variety of data sources and in relation to the goals of individual managers and society at large. Implementation of particular options will depend on the availability of resources, policy instruments, etc. Monitoring and evaluation is an essential part of the process, which not only assesses the success of a project in relation to the stated goals, but also feeds back to the response model (modified from Hobbs & Saunders 2001).

This is where the requirement for ecological response models becomes apparent. These models can be simple or complex, quantitative or conceptual, but they need to capture the essence of the system and its dynamics. Here again, there needs to be consideration of both general characteristics of ecosystems and more specific elements relating to specific cases. A general feature of many systems seems to be the potential for the system to exist in a number of different states, and the likelihood that restoration thresholds exist, which prevent the system from returning to a less-degraded state without the input of management effort (Hobbs & Norton 1996). Whisenant (1999) has recently suggested that two main types of such threshold are likely: one that is caused by biotic interactions, and the other caused by abiotic limitations. Figure 3a illustrates these two thresholds and indicates that the type of restoration response needed depends on which, if any, thresholds have been crossed. If the system has degraded mainly due to biotic changes (such as grazing-induced changes in vegetation composition), restoration efforts need to focus on biotic manipulations which remove the degrading factor (e.g., the grazing animal) and adjust the biotic composition (e.g., replant desired species). If, on the other hand, the system has degraded due to changes in abiotic features (such as through soil erosion or contamination), restoration efforts need to focus first on removing the degrading factor and repairing the physical and/or chemical environment. In the latter case, there is little point in focusing on biotic manipulation without first tackling the abiotic problems.

The above argument is akin to ensuring that system functioning is corrected or maintained before questions of biotic composition and structure are considered. Considering system function provides a useful framework for the initial assessment of the state of the system and the subsequent selection of repair measures (Tongway & Ludwig 1996; Ludwig et al. 1997). Where function is not impaired, restoration can legitimately focus on composition and structure as parameters to be considered when setting goals.

The same scheme can be considered at a landscape scale. Hobbs and Norton (1996) and others have emphasized the need for restoration ecology to develop effective approaches for broad-scale restoration at landscape and regional scales. At broad scales, however, it

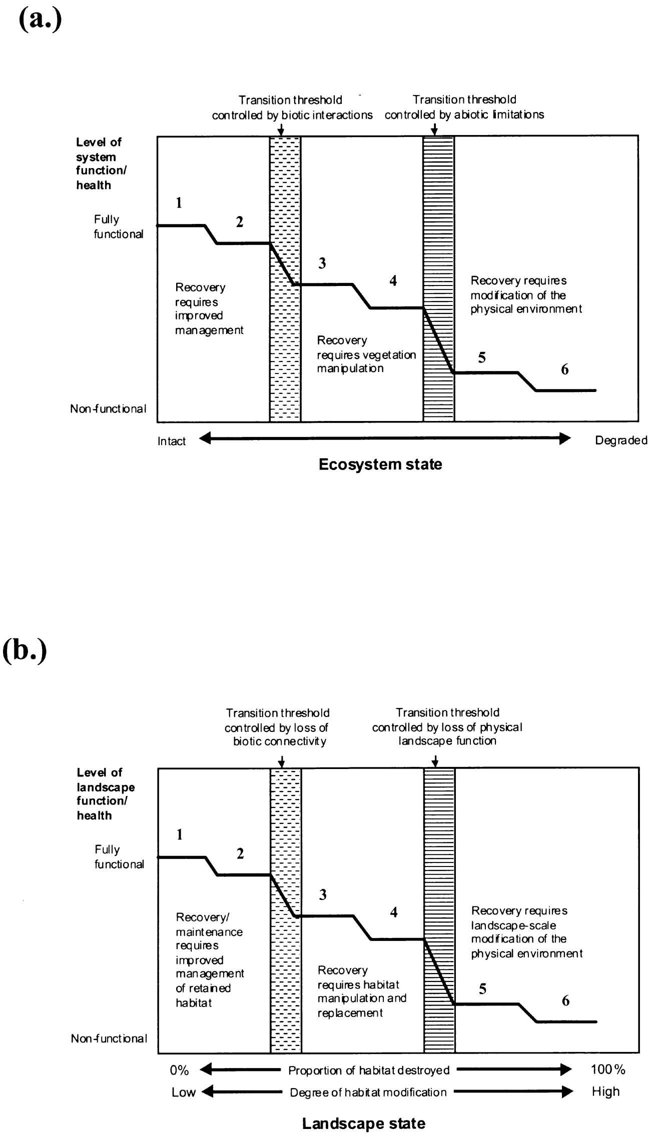

Figure 3. (a) Conceptual model of system transitions between states of varying levels of function, illustrating the presence of two types of restoration threshold, one controlled by biotic interactions and one controlled by abiotic limitations (adapted from Whisenant 1999). (b) A similar model applied to landscapes, indicating transition thresholds controlled by loss of biotic connectivity and loss of physical landscape function.

becomes even more difficult to decide what should be restored, where and how. Attempts to focus on key landscape attributes have so far provided many possible parameters (Aronson & Le Floc'h 1996*b*), but not much of a framework in which to set priorities and goals. We suggest that a start can be made on this by considering whether restoration thresholds exist at the landscape scale. It can be hypothesized that similar threshold types might exist at this scale as are apparent in particular ecosystems or sites (Fig. 3b). Thus, one type of threshold relates to the loss of biotic connectivity as habitat becomes increasingly fragmented and modified, while another relates to whether landscape modification has resulted in broad-scale changes in landscape physical processes, such as hydrology. Here again, this schema can assist in setting restoration priorities. If the landscape has crossed a biotic threshold, restoration needs to aim at restoring connectivity. If, on the other hand, a physical threshold has been crossed, this needs to be treated as a priority. Hence, for instance, in a fragmented forested landscape, the primary goal may be the provision of additional habitat or reestablishing connectivity for particular target species, whereas in a modified river or wetland system, the primary need may be to reestablish water flows (Middleton 1999).

Of course, within these broad categorizations, there may be numerous sub-categories and thresholds. For instance, McIntyre and Hobbs (1999, 2001) have recently explored how to categorize landscapes in terms of the degree of habitat destruction and modification, and hence how to assign management and restoration priorities. It may also be the case that the restoration activities required to overcome particular physical changes also act to overcome biotic thresholds. An example of this would be if extensive revegetation is required to counteract hydrological imbalances, and at the same time can have a positive impact on biotic connectivity (Hobbs 1993; Hobbs et al. 1993).

Once the options for restoration have been derived from an ecological response model, these then have to be considered in the broader context of individual and societal goals. To succeed, restoration activities need not only to be based on sound ecological principles and information, but also to be economically possible and practically achievable. They also have to take their place amongst other options such as providing more resources to protect existing habitats. There is also always the "do nothing" option, which is often the easiest, but not necessarily the most desirable. Often another primary driver in deciding which options will be pursued is the prevailing political climate, which drives government support and funding for restoration activities. Unfortunately, political opportunism often plays more of a part in setting priorities and deciding on options than any rational process.

Measurements of Success

We will not discuss in detail the implementation of restoration projects here, but will consider the need for adequate measures of progress toward agreed-upon restoration goals. These are important for many reasons, not the least of which are the statutory requirements often placed on management agencies, mining companies and the like to demonstrate adequate achievement of stated goals. If we have goals relating to composition, structure, function and the like, what measures do we use to quantify the success, or otherwise, of the restoration process?

There have been numerous attempts to provide categories of assessment that will contribute to a picture of the "healthy ecosystem," which have varying degrees of ease of measurement. Biological potential inventory is probably the earliest form of ecosystem assessment, typified by the species list. This can take the form of a simple list of plant species, extending to complex descriptions of everything from bacteria to avian guild structures, including abundance measurements. Although this can be extremely useful for assessing conservation status, and is greatly improved by measurements over time, it often does not get to the basics of what is causing the degradation, rather simply reflecting the magnitude and direction of its effect. We also need to ask what level of structural/compositional replication we want to set as a goal. We also need to consider how this relates to normal successional processes (Parker 1997). If the goal is to speed up system development beyond what would happen without intervention, how fast is fast enough, and can we compare different trajectories effectively? Can we be sure that a trajectory model for system development is appropriate (Zedler & Callaway 1999)?

More complex measurements of biological integrity can assess food-web complexity and the development of symbiotic relationships. However, difficulty of assessment increases greatly. Measurements relating to ecosystem function can include measurements of production, standing crop, mass balance and mineral cycling pools, particularly fixation, mineralization, immobilization and "leakiness." The problem with all these measures lies in determining what the target should be, in relation to the problems discussed above concerning reference systems.

Other more abstract possibilities may be worth pursuing. For instance, the concept of entropy points to a gradual decline in order in all systems over time (Miller 1971). All living entities remain "alive" by pumping out disorder, i.e., maintaining themselves against thermodynamic gradients by taking in energy and locally reducing the production of entropy, by organizing small molecules (mineral ions and gases) into large ones (organic molecules and DNA). Similarly, human activities in maintaining production systems aim to impose order, but frequently succeed in increasing disorder in the surrounding environment. Addiscott (1995) has suggested that an audit of small versus large molecules (a ratio) may be useful as a measurement of sustainability, and hence also as a measure of restoration status. Therefore, in an efficient system, small molecules should persist for only short periods before being reassimilated by the biomass. In addition, any gaseous losses should be balanced by uptake. These parameters are readily amenable to measurement. This may be achieved by careful measurement of the rates of flux of small molecules from a site, combined with an estimation of how much material is bound in the living biomass. This then offers a true "systems condition" parameter with which to gauge success.

A potential index for use in tracking restoration is that of "1/f noise." 1/f noise is the signal that emerges when the rate of change in a parameter of a system is measured. For example, if the rate of change in the height of the water table in a peat bog is measured, and the reciprocal of this rate plotted, then the 1/f power relationship results. This reciprocal signal of rate fluxes can be found in a range of phenomena as diverse as traffic flow, evolutionary extinction rates and stock market price fluctuations (Bak 1997), and indicates that the system is fluctuating "efficiently." We can measure rates of change in water levels, fixation rates, nitrogen fluxes and population sizes. In natural systems we should get 1/f noise signals. Therefore, one concrete aim of a restoration would be to "restore" this signal.

This treatment of how to measure the progress of restoration projects has, like most others in the literature, been superficial and poses more questions than it answers. We suggest that measures of success have to be linked back to clear definitions of goals for restoration. Assessment processes can be complicated and expensive, and if they are too complicated or expensive, they will not be carried out. There is no point in assessing something unless it relates to specific goals. If the restoration goal is to "reestablish a diverse vegetation cover resembling that present before disturbance," we do not know how diverse is diverse enough, how closely the vegetation needs to resemble the pre-disturbance vegetation, and in all likelihood do not have a clear picture of what the pre-disturbance vegetation was anyway. Any assessment process will thus produce equivocal results. If, on the other hand, we have as a goal "to reestablish vegetation with a woodland structure of 20 trees per hectare, comprising local provenance native species which attain a height of at least 2 m within 5 years, and an understory of native shrubs, forbs and herbs achieving a site diversity of 25 +/− 6 species," we can then start to measure the actual performance of the restoration in these terms. This goal can be set in relation to data on the pre-existing vegetation, or to the composition of adjacent vegetation, or can be settled on by discussion with stakeholders about what may be possible and desirable on the site.

Putting This into Practice

The start of the new millennium is a good time to take up a challenge. There are plenty of challenges facing humanity in this new era, and here we have focused on the particular challenges facing restoration ecologists. We present the challenge to restoration practitioners and scientists alike to get our act together and devise and deliver effective restoration strategies and practices which can help repair the widespread ecological damage left to us from the last millennium. We need effective interaction between scientific analysis, land-user innovation and the development of principles. We need effective links between academics, practitioners and policy makers at all levels. We need the translation of research findings into action, and continuous feedback between users and researchers. We need to make sure that our actions are based on the best knowledge available now, and that managers have up-to-date paradigms in their heads when they act. At the same time, we need to ensure that researchers ask questions that are relevant to the real world. It has been argued that this could form part of an on-going professional accreditation program (Harris 1997).

Restoration ecologists cannot find all the answers by themselves. Indeed, it is not our place to answer all the questions relating to what restoration goals should be and how they should be achieved. These discussions need to be held more broadly within society. What we can provide, however, is input to this discussion in relation to the ecological validity, costs and likelihood of success of various restoration options. Restoration ecology provides positive hope for the future, and hence restoration ecologists have a weighty responsibility to ensure that our science and practice live up to expectations.

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