

Underlying principles of restoration

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Abstract: The term restoration is used in many ways; however, it normally implies return to an original state. In ecological restoration, it should be thought of as applying to whole ecosystems. It must be remembered that options, such as rehabilitation or replacement, exist that may be more practicable than restoration. The components of restoration are the chemical and physical aspects of the habitat and the species themselves. Each of these may require specific treatment, but natural restorative processes should be used wherever possible; in fact, natural processes may be sufficient once the degrading influences have been removed. Because the process of restoration is progressive, the criteria of success are not easy to define. The most important point is that ecosystem development should be on an unrestricted upward path. From this, it follows that successful restoration is a serious test of our ecological understanding.

Résumé : Le terme restauration est utilisé dans plusieurs sens, mais il suppose normalement un retour à l'état initial. Dans le domaine de l'écologie, il faut voir la restauration comme s'appliquant à des écosystèmes complets et se souvenir que d'autres solutions, comme la réhabilitation et le remplacement, peuvent être plus réalistes. La restauration vise à la fois les aspects chimiques et physiques de l'habitat et les espèces elles-mêmes; chacun de ces volets peut exiger des mesures particulières, mais il faut autant que possible se fier aux mécanismes naturels de restauration. En fait, si on a éliminé les sources de dégradation, ces mécanismes sont souvent suffisants. Comme la restauration est un processus progressif, il peut être difficile de fixer des critères de réussite. Il faut avant tout se rappeler que l'écosystème doit se développer sans entrave dans le sens d'une amélioration. La réussite d'une telle opération met à rude épreuve notre compréhension de l'écologie.
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Introduction

There is a tendency for individual groups involved in the practical aspects of restoration to pay little attention to what others are doing, or have done. The reason is usually that they feel that their problem is special and has little connection with others, because of climate, terrain, species, or any of the many other ways one community can differ from another. Yet the strength of modern ecology is that it has been able to produce underlying principles of general application.

In restoration ecology it is clear that general principles are developing that are applicable widely, no matter whether the subject is the restoration of tundra, tropical forest, lakes, or farmland. Because the HabCARES workshop is mainly about aquatic systems and this paper is by an ecologist whose main experience is in terrestrial systems, the challenge is to show that generalizations are possible and can provide valuable guidance to restoration practice.

What is restoration?

We must be clear what is being discussed. Although words can change their meaning, it is important to examine what they have meant until recently (here using Oxford English Dictionary; Fowler and Fowler 1971). The relevant definition of *restoration* is "the act of restoring to a former state or position ... or to an unimpaired or perfect condition." To *restore* is "to bring back to the original state... or to a healthy or vigorous state. There is both the implication of returning to an original

state and to a state that is perfect and healthy. This seems to be the way in which we continue to use the word on both sides of the Atlantic.

Rehabilitation is defined as "the action of restoring a thing to a previous condition or status." This appears rather similar to restoration, but there is little or no implication of perfection. Indeed in common usage, something that is rehabilitated is not expected to be in as original or healthy a state as if it had been restored.

Remediation is the act of remedying. To remedy is "to rectify, to make good." Here the emphasis is on the process rather than on the endpoint reached.

Reclamation is a term used by many practitioners, especially in Britain but also in North America. It is defined as "the making of land fit for cultivation." But to reclaim is given as "to bring back to a proper state." There is no implication of returning to an original state but rather to a useful one.

Replacement is, therefore, a possible alternative option. To replace is "to provide or procure a substitute or equivalent in place of" (although an alternative meaning is to restore).

Mitigation is a word often used when restoration is considered. It is important to note that it is nothing to do with restoration. To *mitigate* is "to appease... or to moderate the heinousness of something." So although mitigation can be an outcome of restoration it is a separate consideration.

Since the word restoration has been adopted for the title of this workshop, it will be used as the point of reference, despite its troublesome perfectionist implications (Francis et al. 1979).

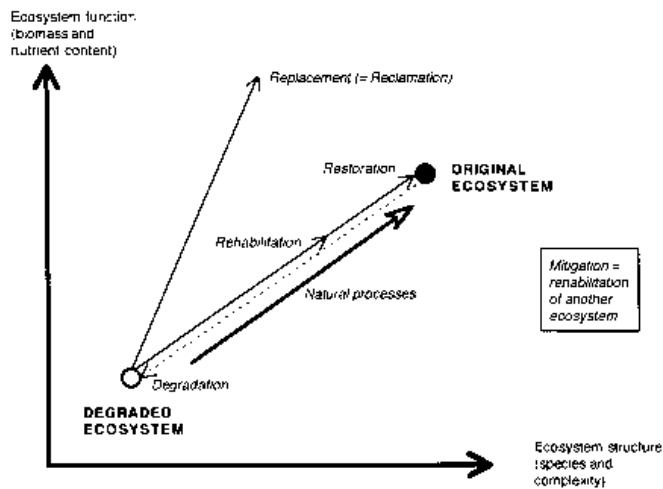
To what are these words applied?

This problem must be addressed because here is where perhaps the greatest confusion lies about what we are doing. From our biological point of view we can apply it to ecosystems, habitats, communities, species, water or soil quality, or some other

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Fig. 1. The several different options in remediation work.



characteristic of the degraded or damaged area. All these are different, and therefore, their use has specific implications.

The word *ecosystem* covers the biological and nonbiological elements occurring together in a particular area. So it is all inclusive. However, because “system” is included, there is an emphasis on the overarching functions and interactions of these elements. So when the restoration of *ecosystems* is being referred to, the suggestion is that we are particularly interested in the restoration of the fundamental processes by which ecosystems work. This has been well argued by Cairns (1988).

It is common now to talk about *habitat* restoration; it is in the title of this workshop. Because habitat refers just to the place where organisms live, it tends to imply less than ecosystem. Its use, therefore, puts more emphasis on the restoration of place than of important ecological functions. We can also talk about restoration of *communities* or of *species*. In this case the emphasis is on just the plants and animals occurring in a particular place, or on a single species.

We also talk about restoration of *quality*. This is particularly true in discussions of soil or water restoration, perhaps because the species in these habitats are multifarious and their individual occurrences difficult to predict; therefore, the implication is different. It is the perceived attributes of what is in an area, or of a component of the environment, that are considered to be important. To what is referred depends on the particular situation; it could be either an important factor, such as biological oxygen demand or level of contaminants, or a derivative of well being such as species diversity.

Whatever we may think deserves attention, our intention should always be to focus on the restoration of functions, of processes, because without this the communities of organisms in which we are interested cannot persist. Our ultimate aim should be the restoration of the whole ecosystem, even if we sometimes emphasise some particular component or attribute (National Research Council 1992, Ch. 1).

Options in restoration

There are clearly many attributes to an ecosystem. These can usefully be simplified into two main components: structure

and function. What has happened in a damaged ecosystem can then be represented graphically with these components as the two axes (Bradshaw 1987a) (Fig. 1). Both components will have suffered and will have to be restored. Rehabilitation, in which progress has been made but the original state not achieved, and reclamation, to something different, can be represented on the same figure.

This clarifies our options. In particular it points to the fact that restoration may not be easy. It may be possible, perhaps, to restore the functions fairly completely, but to achieve the original structure may be more difficult. This may not be so true in an aquatic ecosystem where, because of the smallness and consequent mobility of the individuals, the rate of reestablishment of populations can be rapid, but it will certainly be impossible to achieve in less than 500 yr. It may not be possible to achieve an original soil profile in less than 5000 yr, although the biological functions of a soil can perhaps be restored in less than 10 yr.

So in many situations, true restoration may be unrealistic. It may also be impossibly expensive. So we should realise that rehabilitation and replacement can be proper options. Both these alternatives, by offering something different, may provide an endpoint that is more valuable than what was there in the first place. Replacement is a particularly interesting option since it may allow restoration of a component, such as productivity, to a higher level than existed previously. In the heavily developed agricultural land of Britain, sand and gravel workings left to fill with water have contributed enormously to the diversity of wildlife and landscape in many areas. This is valuable reclamation; however, it is not true restoration although there may be restoration of particular attributes such as biodiversity.

It is, therefore, very important that when any work is undertaken, the different options and what they each might involve are clearly worked out and understood. Figure 1 can provide useful guidelines. The endpoint of full restoration, although it may seem ethically the most justifiable and, therefore, the most obvious to adopt, may in fact not always be the most sensible in practical or biological terms.

Components of restoration

To judge what is worthwhile attempting it is necessary to appreciate what it involves. In essence, no matter what ecosystem is being tackled, once the damaging process has been controlled, the crucial characteristic of any intervention is that it should relieve those factors that are restraining the redevelopment of the ecosystem required. Obviously this can involve many different elements, depending on the ecosystem and the degradation that has occurred.

Essentially three matters will need attention: (i) remodelling the physical aspects of the habitat; (ii) remodelling the chemical aspects, nutrients, and toxicity; and (iii) replacing missing species or removing undesirable exotics.

Exactly what is required will depend on what is wrong. For instance, acid land left after coal mining will require liming; raw inert materials left to be soils will require nutrients; lakes overcharged with phosphorus may require mud pumping; lost species may require reintroduction. There are now handbooks as well as papers on all these and other problems (e.g., for land,

Coppin and Bradshaw 1982; Lyle 1987; Schaller and Sutton 1978; Williamson et al. 1982; for water, National Research Council 1992; Ryding and Rast 1989; for the Great Lakes, Francis et al. 1979). It is possible to rationalize what is to be done (e.g., for terrestrial habitats, Bradshaw 1987a; for lakes, National Research Council 1992, Ch. 4). Attempts are now being made to put this rationale into logical decision trees (Maguire 1988). It is essential to identify the controlling factors that will not ameliorate naturally and then address these first.

Use of natural processes

These recommendations may suggest that each fault or deficiency has to be addressed if restoration is to be achieved. Yet we all know that, in the Great Lakes region, the preexisting vegetation and soils were repeatedly destroyed by the great ice sheets that covered much of North America. When these retreated, natural processes were able to build up ecosystems to their present day complexity of structure and function. The different processes, covered by the omnibus term "primary succession," have been well described recently (Miles and Walton 1993). These same processes are visibly at work in the secondary succession that follows present-day disturbances, whether in old fields, tropical forests, or other situations (Gray et al. 1987). They are processes of considerable power; they can bring about major changes in time scales as brief as decades and are particularly applicable to large ecosystems such as the Great Lakes.

With such a series of natural processes that can be harnessed to help restoration, we have to decide what part they should play in our work. It should be axiomatic that they should be used wherever possible, firstly because they cost nothing in themselves (although they may cost something to initiate); secondly, they are likely to be self sustaining because they originate from within nature (although they may need nurturing in some situations); and thirdly, they can be used on a large scale. Although it is clear that natural processes can eventually achieve full restoration, some may take a long time and need to be assisted. It is not possible to describe all the ways in which natural processes can be used, but some illustrations can be made.

Physical problems

Many degraded soils and deposited materials are compacted and have a high bulk density. Yet the changes that take place naturally on glacial moraines (Crocker and Major 1955), as well as on coal waste heaps and elsewhere, show that radical changes can be brought about by the growth of vegetation, the incorporation of organic matter, and the activities of soil fauna and flora. However, in some seriously compacted situations, natural recovery is so slow that mechanical treatment is necessary. In aquatic systems, physical treatments are widely undertaken.

Nutrient problems

One of the commonest problems of degraded terrestrial environments is lack of nutrients, particularly nitrogen. The soil nitrogen capital, normally at least 1000 kg N-ha⁻¹, can be rebuilt up by means of fertilizers, but this is expensive and involves returning many times. It is much simpler to introduce

legumes, such as white clover *Trifolium repens*, which can accumulate nitrogen at the rate of 100 kg N-ha⁻¹·yr⁻¹. However, calcium and phosphorus levels must be sufficient to maintain the growth of the clover (Roberts et al. 1982), although N-fixing species can often be chosen that do not have as special nutrient requirements as clover. By contrast, nutrients such as phosphorus cannot be conjured out of the air and will remain deficient if not added.

In aquatic systems the problem is usually excess of nutrients. Once inputs into flowing systems are stopped, recovery is usually rapid. But this does not occur so readily in lakes. For lakes of limited size the removal of the nutrient-rich bottom muds may be possible. In other situations a totally different approach, using natural ecological processes that involve the manipulation of phytoplankton by manipulation of the zooplankton (Moss 1992; Hospers and Meijer 1993), can be more effective. The fact that assisting the growth of protective macrophytes or even the provision of bundles of twigs, to provide safe sites for the zooplankton, is effective, challenges our understanding of the mechanics of the freshwater ecosystem. Unfortunately, the size of the Great Lakes make both these approaches impractical; natural dispersal and loss may be the only answer.

Toxicity

This can be one of the most intractable problems, which natural processes by themselves cannot easily overcome, as witnessed by the persistent degraded and often completely bare areas contaminated by heavy metals in many places in the world (Ernst 1974). Yet restoration of the northern deciduous forests destroyed by the nickel smelters at Sudbury, Ont., illustrates both the problems and possibilities (Gunn 1995). Earlier work suggested that the combination of acidity and metal toxicity could only be answered by the use of metal-tolerant grasses. However, once the acidity is relieved by liming, the metal becomes less available and trees, which root through the surface soil into the less polluted horizons below, can be planted. Once such trees establish, the development of the ecosystem takes a new direction. Surface conditions are ameliorated sufficiently for natural recolonization to occur. In the end, elevated metal levels may remain, but a fully functional forest seems certain to develop. On a smaller scale a vigorous grassland ecosystem has been developed on lead-zinc mine tailings following an initial stimulus of sewage sludge and fertilizers (Johnson et al. 1976).

In aquatic habitats, once the toxic input has ceased, natural processes can lead to recovery even where the toxicity defies treatment. This is well demonstrated by the progressive reduction in metals in the Mersey Estuary that has occurred since inputs have been reduced over recent decades (National Rivers Authority 1995). Acid rain can be a serious problem because whole catchments are affected. To reverse the effects, liming of lakes has been carried out, but such localized treatment has usually had only short-term effects. The logical answer is to treat the source of the problem and lime the catchment rather than the lake. Work on this has so far been very promising (Howells and Dalziel 1992). It is important to note that except for liming and reintroduction of missing fish species, everything else can be left to natural processes.

Species

Because of the dispersal powers of many species it is easy to fall into the trap of thinking that natural processes can be relied on for all species. In terrestrial situations, if rapid establishment is required, sowing of the main plant species is always essential. It is then often presumed that other species will arrive on their own. But studies of the recolonization of chemical wastes over the last 100 yr show that several appropriate species are missing because their nearest populations are too far away (Gray et al. 1994). The herbaceous species of woodlands are notoriously poor at dispersal (Peterken 1974); therefore, it can be crucial to introduce the missing species by artificial means (Francis 1993). The comparisons made between intervention and leaving natural processes alone to achieve recovery at Mount St. Helens are particularly interesting (Franklin et al. 1988); intervention certainly leads to more rapid recovery, especially where destruction of the habitat has been most complete.

In aquatic systems the situation is different. Fish, of course, will often need transfer. But most of the important species are microscopic and easily dispersed. Natural dispersal processes are, therefore, usually effective, especially in streams and lakes where substantial transport processes exist. This may not be true, however, for new isolated water bodies. In one of the earliest and very successful attempts to create a new aquatic system for the conservation of wildfowl from a gravel pit, there was no need to introduce the wildfowl, but the water body was inoculated with aquatic plant and animal species by bringing in species-rich mud (Harrison 1974). This is now recommended practice (Andrews and Kinsman 1990). Note that it is inoculation that is suggested, not full-scale planting, since natural processes of species establishment and spread will take the developing ecosystem on to its mature state. The removal of species, usually of alien introductions such as the sea lamprey (*Petromyzon marinus*), is another problem altogether, unfortunately often impossible to rectify.

Engineering

All this leads us into the whole subject of ecological engineering (Mitsch and Jorgensen 1989) sometimes called bioengineering (Schiechl 1980). The discipline is much wider than the restoration we are considering here, being described as the techniques of designing and operating the economy with nature (Odum 1989). But within it are many provocative examples of how ecological processes can be harnessed specifically for the purposes of restoration, particularly in civil engineering situations.

In any restoration situation it is important to become fully aware of the natural processes already occurring. This may mean detailed studies of primary succession in the damaged area or in analogous areas. The detail is important, as a mere record of species colonization may tell very little. In both aquatic and terrestrial situations it will be valuable to understand matters such as the origins of the immigrating species, the part played by safe sites for species establishment, the changes occurring in soil or water fertility and in microorganisms, and the effects of species interactions. It can be informative to study the factors that appear to be preventing succession (Gemmell 1975). There is a complementarity between academic and practically oriented ecological studies; this is discussed later.

The possibility of doing nothing

The contribution of primary succession and natural processes introduces an alternative possibility, the extreme option of actually doing nothing. This can be seen as the negation of restoration. If, however, natural processes of primary or secondary succession are powerful, they may be able to do all that is necessary. Certainly the forested fields of New England are witness to the power of old-field succession.

If restoration is used in a wide sense to include the restoration of biodiversity, then untreated areas may have an important place in the different strategies of restoration. In Britain, disused quarries are now recognised as being important additions to the countryside because, in their unrestored state, they provide havens for species that find it difficult to survive in the managed agricultural countryside (Ratcliffe 1974). Restrictions on ecosystem development can, indeed, be an advantage for some species.

Similarly, young lakes can be important. Gravel pits have allowed the development of previous threatened floras and the spread into Britain of the little ringed plover. In Indiana, strip mine pits and ponds have had an important role for wildlife, sufficient to make it important to develop methods of modifying them, but not destroying them, to increase their wildlife potential (Willard 1988).

The criteria of success

How far, then, should intervention go? Purists, whether among the ecological profession or the general public, may ask for everything to be restored completely. Even if actually impossible, to approach such perfection can be immensely difficult. It has led to planners requiring the transfer, for restoration purposes, of mature forests, which is impracticable. It can lead to immense costs. Certain manipulations, however, such as the retention and replacement of original topsoils, may be the only way to achieve the appropriate endpoint, as in the Australian sand mining industry (Bradshaw and Chadwick 1980). Equally, the total removal of contaminated or highly eutrophic sediments may be the only way to restore the water quality and, therefore, the total ecosystems of some damaged lakes.

But if we are realistic, such major operations may be excessive or impossible in large systems such as the Great Lakes. What is important is to set off succession in the right direction and then leave it to continue itself; this may require preparatory work. Nobody thinks that there is anything wrong in planting small trees to reestablish a forest. But to achieve satisfactory growth it may be necessary to ensure that the soil is fertile or has the means to make it fertile such as by the inclusion of nitrogen-fixing species. This illustrates the importance of ensuring that the functions of the developing ecosystem are properly cared for.

But what are to be the criteria of success? Firstly, should the criteria be based on structure, and in particular the presence or absence of species, or on function, such as plant growth? There is no easy answer, since so much depends on what was the original particular value of the area, and therefore, what is seen to be critical. If the area was rich in wildlife, then the number of species might be the criterion; but if the area was mainly used for agriculture, then crop yield may be the most crucial criterion, as it is in the U.S. Surface Mining Control

Table 1. A checklist of problems to be found in degraded terrestrial ecosystems, any of which may require treatment, by intervention or natural processes, if restoration is to be successful.

Category	Problem
Physical	
Texture	Coarse, fine
Structure	Compact, loose
Stability	Unstable
Moisture	Wet, dry
Nutrition	
Macronutrients	Nitrogen, others
Micronutrients	Deficient
Toxicity	
pH	Low, high
Heavy metals	High
Salinity	High
Organisms	
Plants	Absent, slow colonization, alien species
Animals	Absent, slow colonization, alien species

Note: A detailed checklist should be made for any habitat requiring restoration.

and Reclamation Act (SMCRA). It could, of course, be some much simpler criterion, such as the amount of heavy metal emanating from a mine site, since water quality down stream will be directly related to this figure.

Secondly, if reliance is being placed on the progressive effects of natural processes, what level has to be achieved? Should 75 or 90% of the preexisting species or plant yield be achieved? There can be no fixed criterion for these, although SMCRA expects 90%. Should metal burdens be reduced to 50, 10, or only 1% of what occurred previously? There are again no easy criteria, although for water there are World Health Organization and individual government standards. For a critical element such as phosphorus in lake water we may from experience take a value such as $100 \mu\text{g P}\cdot\text{L}^{-1}$ as the critical level in recovery from hypertrophication (Ryding and Rast 1989). But this begs the question as to what is to be considered the original state; is it to be the water quality of 1930, 1950, or perhaps 1500, bearing in mind that human beings have long been part of the ecosystem? In a recent analysis of English lakes, Johns et al. (1994) suggest the middle 1930s because this is after the full establishment of agriculture but before the advent of intensive agriculture.

Thirdly, once targets have been set, by when should they be achieved? Five years is taken as the period for bond release under SMCRA. But for many natural terrestrial processes such as the accumulation of soil nitrogen, it is not long enough. It can also not be long enough to judge whether interventions are adequate, such as the supply of phosphorus in face of soil phosphorus-fixing processes (Daniels and Zipper 1988). There is no easy answer, except that 3 years is certainly not long enough in either aquatic or terrestrial systems over which to judge success, particularly if restoration has involved major work. What has been done may well last for a few years and then collapse. It was, for instance, not possible to understand the changes taking place in the water quality of the Norfolk Broads, and how they could be combated, in less than a 10-yr

study period (Moss 1989). It has taken a similar period of time to establish that a minimum of $1000 \text{ kg N}\cdot\text{ha}^{-1}$ is required for the restoration of temperate terrestrial ecosystems (Marrs et al. 1982).

It is certainly easier to require the presence or absence of particular species by a certain number of years. This does not need detailed understanding of functions and it is easy to specify. Yet this approach is fraught with dangers, especially if species have been artificially reintroduced. They may persist for a few years and then disappear because the restoration of underlying functions has not been addressed properly.

What is crucial is that the development of the ecosystem should be on an upward path in terms of structure and function (Fig. 1), and that no barriers to its long term further development can be envisaged. It is invaluable to have the potential limiting factors in the form of a check list, for example Table 1. This means that both the environment and the process of ecosystem development must be understood. We must also beware of taking any character as a surrogate for the whole development process. In salt marsh restoration for instance, despite its widespread use, the criterion of increased tidal flushing can be misleading, because of complexities in hydrology (Zedler 1988). Should we really put so much stress on biodiversity?

Restoration as an acid test of our understanding

This brings us to the final point, that there is a close relationship between ecological understanding and successful restoration. Indeed, restoration is an acid test of our ecological understanding (Bradshaw 1987b), because if we do not understand the processes at work in an ecosystem we are unlikely to be able to reconstruct it so that it works.

But the relationship is reciprocal, since any attempt to reconstruct an ecosystem is a test of our knowledge of the ecosystem and will reveal any deficiencies in our theoretical knowledge. It is easy enough to take an ecosystem to bits and think that all the significant attributes have been identified. It is only when attempts are made to put it together again that it can be seen whether the bits have been identified correctly. We can learn from our failures.

There is, however, one problem. When restoration is apparently taking place because of the efforts expended, there is the possibility that it could actually be due to the self-restoring properties of the ecosystem, the processes involved in primary succession that we have already discussed. This confusion can be overcome by careful experiments, in which the effects of intervention are compared with suitable controls where there is no intervention.

This raises the role of experimentation in restoration. Such tests cannot be applied unless proper experiments are set up in which critical comparisons can be made. Comparison is an essential aspect of scientific ecology (Bradshaw 1987c). The efficacy of different forms of intervention can similarly only be examined in proper experiments, with good statistical design. It should be an essential part of every restoration programme that experimental testing of different aspects of the intervention are carried out. In terrestrial ecosystems this sort of experimentation is easy (Bradshaw and Chadwick 1980). In aquatic systems it is more difficult but equally necessary.

Finally, it is essential that results are published in journals or reports that are readily available to everyone working in the field. Reviews, including failures as well as successes, are particularly important. It is only by exchange of information that science progresses and that new findings and ideas can be promulgated and developed. Not only should we not have to reinvent the wheel, but also there are generalizations to be made that will allow us to make predictions to guide future action. The development of the science of restoration should go hand in hand with achievements of successful restoration itself.

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