Restoration ecology

a synthetic approach to ecological research

edited by

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tend to be slighted. While in the absence of detailed historical analysis it is impossible to be sure about this, it seems quite plausible that as a result of something of this sort the contributions the practice of ecological restoration has made to basic ecological research have generally been underestimated.

In the chapters that follow, an attempt is made to explore this area and to consider what ecology may have derived from the experience of restoration, even when the restoration has not been carried out for explicitly experimental purposes. Represented here are communities of several types, and a general discussion by Anthony Bradshaw of the ecological value of restoring ecosystems that have been profoundly disturbed as a result of operations such as surface mining.

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5

The reclamation of derelict land and the ecology of ecosystems

Anyone who sets about to repair or restore any object, whether it is a clock, an old engine, or an eroded savanna, soon realizes that in order to do a good job he or she needs to know something about that object, the nature of its parts, how it was put together in the first place, and how the whole thing works. There is nothing subtle about this. Even the simplest repair demands some basic understanding, and the successful repair of a complex object may require a very detailed understanding (Fig. 5.1).

But repair or restoration really has two stages. The first is to discover and understand what is wrong. The second is then to put it right correctly and appropriately. How often are repairs of everyday objects unsuccessful because the repairer does not understand what is wrong or, having understood what is wrong, fails to make the repair correctly? As a result the repaired object either fails to work at all or fails again very quickly.

It is essential that we keep this analogy in mind when we approach any problem of land or ecosystem restoration. Like watch repair, restoration is a considerable intellectual challenge requiring that we understand not only the nature of the ecosystem itself, but also the nature of the damage and how to repair it. Hence my assertion in an earlier chapter that land restoration is an acid test of our ecological understanding. But there is a reverse side to this. What is discovered by experience to be critical for successful land restoration will also often be a critical contribution to ecological theory.

An examination of restoration practice should, therefore, have considerable heuristic and didactic value. Nowhere is this more apparent than in the reclamation of land that is so degraded that it can be termed derelict. Examples include mine wastes, surface mines where the soil has not been replaced, refuse disposal sites, urban clearance areas and old industrial sites. In many cases on such land the whole ecosystem has disappeared, not just the biotic part but the soil as well. It is the ecological challenge of reclaiming such sites that will be considered in this chapter. However, before we can appreciate what this reclamation can contribute to our ecological understanding, we must realize that many professions can be involved. These represent a variety of approaches and points of view, some of which may be quite different approaches from those of ecologists.

Fig. 5.1. Though often regarded as a purely technical challenge, the restoration of profoundly disturbed ecosystems provides unique opportunities for basic ecological research. Here, ecological restorationists study plantings of prairie species on a site covered by mine tailings in central Wisconsin (photograph by George F. Thompson, courtesy of Tom Hunt, Wisconsin Department of Natural Resources).

Starting points

To many people, especially civil engineers, the reclamation of derelict land is really nothing grandly scientific. It is a simple *technical* problem, a matter of finding permanent economical ways of achieving a few simple objectives: (1) stabilization of land surfaces, (2) pollution control, (3) visual improvement, and (4) general amenity, in order to preserve the structures in which they are interested and to prevent the land from being unpleasant to the people that use it. Also, since the land itself has value for what it can produce, we can add (5) productivity as a possible extra objective. Finally we can take on the more ambitious task of actually restoring the ecological communities that were present originally. This means adding (6) diversity, (7) species composition, and (8) ecosystem function.

In any particular situation only one or two of these objectives may have to be met. Highway engineers, for instance, are looking only for stabilization and visual improvement, but Australian mineral sand miners are looking not only for these but also for everything else, because they are required to put back exactly what was there previously and to ensure that it functions properly. All of these examples constitute land reclamation, but only the latter can be considered as full restoration.

There is a considerable difference, however, between recognizing an objective and understanding how to achieve it. To achieve any or all of these objectives, we are presuming that vegetation will be employed (although it must be remembered that there may be other solutions, such as a layer of concrete). And if vegetation is to be developed, then the matter is essentially an *ecological* problem – that of the reconstruction of ecosystems – because that is what will exist if stable, self-sustaining vegetation is achieved.

This vegetation will have two basic qualities: first its structure, and second its functioning. The structure, measured in terms of species diversity and physical and biological complexity, can be simple – a monospecific salt marsh grass sward, for example. Or it can be as complex as a tropical rainforest or a South African fynbos heathland. Similarly, the functioning or ecological "metabolism" of the system, usually measured in terms of processes such as productivity and nutrient cycling, can be low or high. In any case, to put all this back together in working order is a considerable challenge.

Where land has been destroyed by mining or a similar activity, what is left is something exceedingly basic – just the raw materials, the skeleton from which a soil can be formed, and which, with plants and animals, will develop into an ecosystem. Ecologists will recognize that this process of development, whether it is allowed to occur naturally or is artificially assisted, is the process of "primary succession". We can represent what is involved ecologically in land restoration by a simple, two-dimensional graph (Fig. 5.2) originally proposed by Magnuson *et al.* (1980) and developed subsequently (Bradshaw, 1984). Despite the obvious simplification, this graph has merit because it provides a much needed ecological perspective on restoration practice, and also because it distinguishes the different forms that reclamation of degraded land may take.

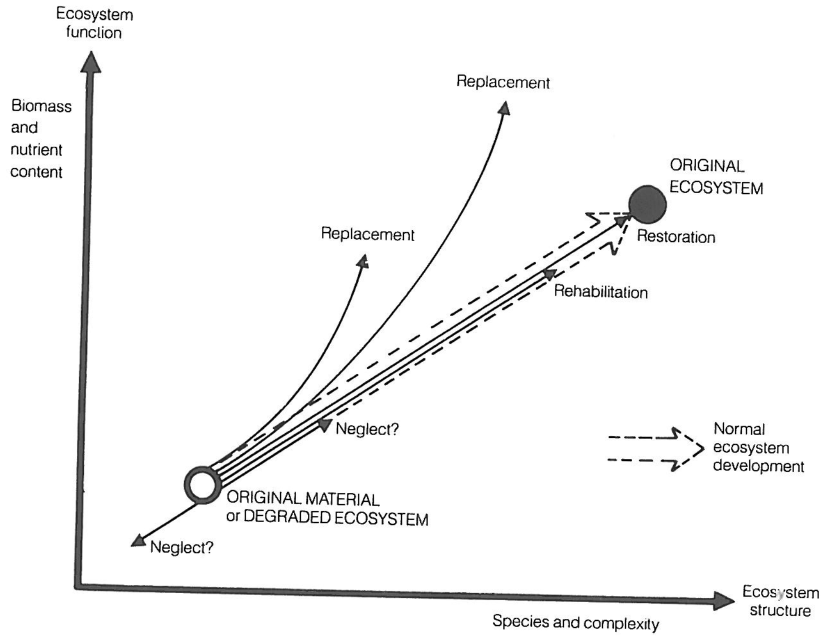

Fig. 5.2. Ecosystem development can be quantified in two dimensions, structure and function. In natural succession there is an increase in both dimensions. When ecosystems are degraded by mining or other operations, there is reduction in both dimensions, perhaps almost to zero. The first option with such a degraded or derelict ecosystem is to do nothing, in which case it may recover slowly by natural processes, though it may also degrade further by erosion or landslip. The second option is to try to build back exactly what was there before. If this is successful then what is achieved is "restoration". If it is not completely successful then what is achieved can be termed "rehabilitation." The third option is "replacement", in which an alternative to the original ecosystem is produced. This could be simpler in structure but more productive (replacement of a woodland by an agricultural grassland, for example). Or it could be simpler and less productive (if, for example, the woodland were replaced by an amenity grassland). The crucial point is that any development of an ecosystem on degraded or derelict land will require carefully planned assistance if the development is to occur quickly (Bradshaw, 1984).

In some situations the degradation of the ecosystem may not have been complete, and the soil may have been left partially intact. In this case, we would be dealing with the process of *secondary succession*. On the graph the starting point would be further from the origin, so there would be less distance to progress to reach the desired endpoint.

But we must also consider land reclamation from a practical point of view. In almost all operations, whatever the endpoint, the following are important considerations: (1) speed of attainment, (2) cheapness, (3) reliability in attainment and (4) stability (implying no maintenance or minimum maintenance of the final product). Except for speed, nature meets these criteria unassisted through natural succession. In land reclamation it is therefore important for us to understand, and as far as possible to take advantage of, what occurs in natural successions, since our aims are generally modeled on the achievements of nature. Equally, however, the reciprocal applies. In ecology it is important for us to understand and to incorporate into our theoretical ecological framework what is found to be successful and important in land restoration, since what is found to be important must be a crucial determinant in ecosystem functioning. In this way ecosystem reconstruction should be a meeting place between practitioners and theorists.

Yet, as in agriculture, until recently there has been a great divorce between these two approaches. To be blunt, ecologists have thought of land reclamation as beneath their dignity, and land reclaimers have not seen any value in an ecological approach. This is unfortunate because, on the one hand, ecologists have missed opportunites to enlarge and test their theories, and on the other hand, land reclaimers could have been saved unnecessary costs and even failures.

This duality and reciprocity becomes clear when the actual steps of the reconstruction process are considered in more detail.

Problems in the reconstruction process

The starting point must be the soil, or at least the substrate into which plants must establish and root, for although soil can exist without plants, there are few plants that can exist without soil. This starting material is usually extremely skeletal on derelict sites, and its properties and situation determine in a very crucial manner the degree to which an ecosystem can develop naturally on the site, how far this development will progress, and what treatments are necessary to assist its development.

Although there are vast numbers of starting materials, ranging from rock faces left by limestone quarrying to red mud produced by aluminium refining, occurring in situations from tundra to tropical forest, the problems they pose can always be reduced to four (Table 5.1). The universality of this table is important in view of the fact that reclaimers often insist that their own problem is unique. It reflects the very simple needs of plants for: (1) a medium into which they are physically able to root, (2) an adequate water supply, (3) an adequate nutrient supply, and (4) lack of toxicity.

One of the simplest ways by which it is possible to see the importance of these factors is by examining the natural colonization that occurs on the poorest of materials. Both colonization and ecosystem development are always slow on severely degraded substrates. However, they are not usually any slower than the same processes occurring on similar materials of natural origin, such as on the glacial moraines so well described by Crocker & Major (1955), where woodland appears in 30–70 years. Similar speeds of development have been found on ironstone wastes by Leisman (1957), and on kaolin wastes by Roberts *et al.* (1981).

However, in several instances ecosystem development can be much slower. Woodland may not appear even after 100 years on some colliery spoils in England (Hall, 1957), and also on lime wastes from the Leblanc process (Bradshaw, 1983). In these cases the slowness of the succession can be attributed to specific arresting factors: very low pH on the colliery spoil and extreme phosphorus deficiency due to high pH and high calcium concentration on the lime wastes. In quarries, Park (1982) has shown that certain combinations of drought and surface texture can result in dramatic reductions in colonization rates. Such situations are completely analogous to what can occur naturally. For instance, on the raw materials of the new volcanic island of Surtsey, large parts still have no higher plants ten years after the island's formation. Part of this is due to difficulties of immigration, but much of it is due to the extreme nature of the volcanic substrates (Fridriksson, 1975).

Table 5.1. *The underlying problems of derelict land and their treatment (from Bradshaw, 1983)*

Category	Problem	Immediate treatment	Long-term treatment
Physical			
Structure	Too compact	Rip or scarify	Vegetation
	Too open	Compact or cover with fine material	Vegetation
Stability	Unstable	Stabilizer/mulch	Regrade or vegetation
Moisture	Too wet	Drain	Drain
	Too dry	Organic mulch	Vegetation
Nutrition			
Macronutrients	Nitrogen	Fertilizer	Legume
	Others	Fertilizer + lime	Fertilizer + lime
Micronutrients		Fertilizer	
Toxicity			
pH	Too high	Pyritic waste or organic matter	Weathering
	Too low	Lime or leaching	Lime or weathering
Heavy metals	Too high	Organic mulch or metal-tolerant cultivars	Inert covering or metal-tolerant cultivars
Salinity	Too high	Weathering or irrigation	Tolerant species or cultivars
Plants and animals			
Wild plants	Absent or slow colonization	Collect seed and sow or spread soil containing propagules or plants	Ensure appropriate conditions
Cultivated plants	Absent	Sow normally or hydroseed	Appropriate aftercare
Animals	Slow colonization	Introduce	Ensure appropriate habitat

Where specific limiting (arresting) factors are not obvious, however, as on glacial moraines or on the inert sand waste produced by the kaolin industry in south-western England, succession still usually occurs at a slow rate. This raises numerous questions about what the rate-limiting factors are and how they vary from site to site. If we knew the answers we would perhaps be in a better position to achieve efficient restoration.

Investigations suggest that nitrogen is usually the major limiting factor (Crocker & Major, 1955; Roberts *et al.*, 1981). It is the only nutrient that changes significantly with ecosystem development and that can be shown to be continually limiting (Marrs *et al.*, 1983, and Ch. 16).

But other factors can be equally limiting, or may at least play a part in limiting the rate of ecosystem development. They can be physical, chemical, or biological. One of the most interesting is the biological factor of immigration. It is difficult to believe that the supply of suitable propagules could be important in determining ecosystem development on a patch of degraded land surrounded by a normal varied agricultural countryside. But where the substrate of that degraded land is alien and very different from the natural soils of the immediate region, it is possible that the ecologically appropriate species are just not present in the vicinity. In this situation the only species that will be able to colonize will be those with special powers of long-range dispersal. In other words, these sites have the properties of islands and show similar biogeographic characteristics (Gray, 1982), including a direct relationship between the area of the site and the number of species that come to occupy it. What is crucial is that the whole process of ecosystem development can be held up by the lack of suitable colonists (Bradshaw, 1983), again just as in nature, on new islands such as Surtsey, for example.

This can be tested directly. In recent experiments, a large number of missing species has been deliberately introduced onto alkali wastes in north-western England. Some of these species, notably *Blackstonia perfoliata* and *Rhinanthus minor*, have spread rapidly over the sites, clearly showing that ecosystem development is being held up by lack of colonists. It is interesting to find that other missing species, such as *Primula veris*, either failed to establish or would grow only in the presence of added major plant nutrients, indicating that chemical limiting factors also play an important role (Ash & Bradshaw, unpublished data).

Treatments

Progress in land restoration technology during the past 20 years has been remarkable. There are now very few degraded environments in which the original ecosystem, or an effective substitute, cannot be established. Unfortunately, much of the detailed methodology is available only in special publications, though there are two substantial reviews (Schaller & Sutton, 1978; Bradshaw & Chadwick, 1980). Nevertheless we must not run away with the idea that all such restoration efforts will always be perfect (in the narrow sense). The products may be deficient in either structure or function. And while a study of the way success is achieved is very instructive, encountering difficulties and attempting to account for them may be even more so.

Soil replacement

The simplest treatment for any existing area of degraded land is to disregard its individual problems and import a new soil surface, on which a new ecosystem can quickly be established. In progressive mining operations, it is of course becoming mandatory for surface soils to be conserved and replaced. In the restoration of small, existing degraded areas, the use of a layer of topsoil to cover up whatever is wrong beneath is common practice.

In a crude sense, this may require little understanding of what is wrong with the site, but it turns out that it does raise many interesting questions about soils and about the relationships between soils and plants. Thus we have come to realize that the processes of importing and spreading, or of conservation and replacement, do demand considerable care to ensure that the topsoil and subsoil structures, especially their macrostructure, are not damaged. In most cases the critical factors involved here are drainage and retention of water (Jansen, 1981). But in extreme cases, soil crumb structure, normally built up over a long period by natural soil processes, can be so damaged in the restoration process that rooting is restricted. Although more work is needed in this area, there is already sufficient evidence to make it clear that the relationship between soil structure and rooting depth is of considerable ecological significance. As a result, quite elaborate systems of soil replacement are now being investigated (Department of Environment, 1982), and quite precise recommendations are suggested to obtain maximum productivity in agricultural ecosystems (Coppin & Bradshaw, 1982). What is necessary for other, more "natural" ecosystems has not yet been precisely defined, but all the evidence so far suggests that the soil part of any ecosystem can have important physical properties that ought to be considered more by ecologists (see Ch. 7).

But this is not all, since it is commonly found that the performances (measured as yield) of ecosystems reconstructed on topsoil are inadequate. Experimentation shows that the soil used is unable to sustain vigorous growth unless suppled with extra nitrogen (Bloomfield, Handley & Bradshaw, 1981). This can be due either to deterioration of the soil during storage between gathering and respreading, or to excessive amounts of subsoil being included in material sold as "topsoil". Either way, the fragility of soil fertility, especially in relation to its ability to provide nitrogen, is made very clear by reclamation experience, a point we shall return to later. (Other ecological phenomena that have been clarified as a result of experience with soil handling procedures are discussed in Ch. 14.)

Direct treatment

In many situations, however, soil cannot be imported or replaced, and the material existing on a site has itself to be treated directly to achieve restoration. The range of treatments commonly used is summarized in Table 5.1. These treatments can be very effective in allowing rapid ecosystem development. This is itself very instructive, not just because it shows that ecosystem restoration is perfectly feasible but because it illustrates some of the distinct requirements for ecosystem development. If any of these requirements is not met because a particular treatment is omitted or because it is inadequate, ecosystem development can fail or be delayed. This may seem rather obvious, but the ways in which such failures occur can provide insights into the requirements of ecosystems and their functioning that may otherwise be very difficult to obtain.

Physical treatments

The need to overcome physical factors in establishing vegetation is taken for granted by all practitioners. Considerable efforts are made to loosen subsoil and topsoil by ripping the substrate to depths up to 1 meter. This is then followed by shallower cultivations, to about 20 cm. Finally, the soil surface is carefully prepared to provide a good seedbed, a favorable season is chosen for sowing, and the seed is buried by mechanical means. Such artificial treatments in themselves suggest the critical nature of the seed germination and seedling establishment process. Sometimes these basically agricultural treatments are difficult to apply, however, and a different and in many ways more natural system of sowing is used – the hydraulic seedling technique, in which the seed is spread in a slurry containing water, fertilizer, mulch, and stabilizer. This method is more natural in the sense that the seed is just scattered on the soil surface and not buried. Often, however, the slurry includes extra, unnatural components – the fertilizer, mulch, and stabilizer – which are intended to help seedling establishment. Interestingly, a detailed analysis shows that only the mulch has positive effects. The other components can be profoundly deleterious, especially in their effect on legumes, and when the climate is not optimal (Roberts & Bradshaw, 1985). It is also interesting that in many cases a rough soil surface is better than any other treatment. This fits in with studies on seed-soil surface relationships (Harper & Benton, 1966), and also suggests ways of economizing in seedbed preparation, since a rough soil surface is much cheaper to provide than a finely prepared seedbed.

Subsequent growth of the ecosystem might appear to be rather unrelated to physical factors in the substrate. However, in the reclamation of raw colliery spoil heaps in England, which contain a high clay fraction, it has recently been shown that soil texture, through its effect on structure, can continue to reduce grass yields for many years (Rimmer, 1982; Elias *et al.*, 1982). What happens is that, following careful preparation by ripping and cultivation, the soil collapses back to become a very hard and dense medium through which plant roots cannot easily penetrate. There are, however, natural processes which obviate this, the best example of which comes from the changes observed by Crocker & Major (1955) on glacial moraines in Alaska, where soil has slowly become open and more porous. This is due to incorporation of organic matter and to the activities of soil flora and fauna. It seems that we are only now beginning to appreciate the importance of these changes and have not yet discovered how to harness them for practical use. Yet there is one remarkable experiment on the effects of earthworms on the characteristics of the soils of newly reclaimed polders in the Netherlands that provides clear evidence of what can be achieved. Where the earthworms have been introduced, the surface mat has disappeared and infiltration capacity has increased more than a hundredfold (Hoogerkamp, Rogaar & Eijsackers, 1983; see also Ch. 7).

Nutrient addition

Having dealt with, or at least worried about, physical problems, the practitioner next expects to have to deal with a series of problems connected with nutrient supply. The need for nutrient additions when ecosystems are being reconstructed on skeletal material is obvious. Materials such as mine wastes or subsoils are unlikely to contain any significant quantities of nitrogen in particular, since in most ecosystems nitrogen accumulates in surface soils as a result of biological activity. But other important nutrients such as phosphorus may also be deficient, either in terms of total or available amounts.

It is easy to provide the necessary nutrients by means of ordinary agricultural fertilizers containing nitrogen, phosphorus, and potassium. In fact, the effects of such supplements are nearly always dramatic, making it very clear that ecosystems, even in a juvenile condition, do need considerable amounts of nutrients for growth, and that these substances are likely to be limiting in most of the skeletal materials found on severely degraded land. Moreover, practical experience, including occasional disastrous failures, shows that these nutrients must be provided repeatedly or growth is substantially reduced. This raises an interesting question: why should the nutrient requirement be so persistent?

If a simple factorial aftercare experiment is carried out, in which all combinations of the three major nutrients (nitrogen, phosphorus and potassium) are applied to a newly established ecosystem that has become moribund, nitrogen is almost always found to be deficient. If nitrogen is provided, growth continues, but if in a subsequent year the treatment is not repeated, growth stops (Bloomfield, Handley & Bradshaw, 1982) (Fig. 5.3). The reasons for this continuing need for nitrogen can be discovered by examining the nutrient requirements of ecosystems. These can easily be calculated in relation to various levels of productivity (Table 5.2). An adequate productivity for many ecosystems is about 5000 kg ha^{-1} yr^{-1}, which requires approximately 100 kgN ha^{-1} – more than any other nutrient. But what is unique about nitrogen is not only that it does not occur as a soil mineral, but also that it is supplied by the decomposition of the organic matter contained in the soil. The amount of the mineral nitrogen that would be supplied by different rates of decomposition and different soil capitals can be calculated (Table 5.3). In temperate regions, a typical annual decomposition rate is about 1/16.

From this it follows that to maintain a productivity of about 5000 kg ha^{-1} yr^{-1} in temperate regions, a soil nitrogen capital of about 1600 kg ha^{-1} is required. The exact amount must depend on rates of decomposition and the particular type of vegetation being considered, but this figure is confirmed by what is found in natural successions, although in some situations, such as on kaolin waste, the value may be somewhat less (Marrs & Bradshaw, 1982). In land reclamation the annual fertilizer dressings

Table 5.2. *Annual nutrient requirement for ecosystems with different productivities (Bradshaw, 1983)*

	Nutrient content assumed (per cent)	Production level (kg ha^{-1} year^{-1})			
		1000	5000	10 000	20 000
Nitrogen	2.0	20	100	200	400
Potassium	1.1	11	55	110	220
Magnesium	0.51	5.1	26	51	102
Calcium	0.26	2.6	13	26	52
Phosphorus	0.18	1.8	9.0	18	36
Type of ecosystem		Tundra and desert	Poorly productive temperate	Productive temperate and poorly productive tropical	Tropical

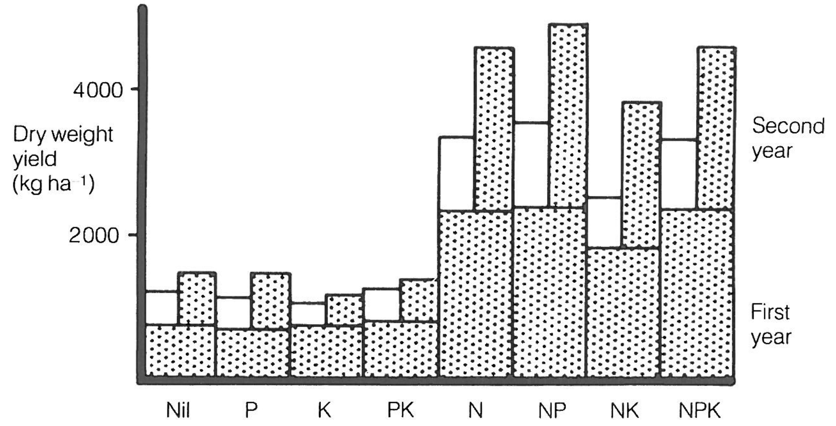

Fig. 5.3. When almost any ecosystem has been established on very degraded soils with the assistance of fertilizer treatments, growth declines dramatically if these treatments are terminated after one or two years, which is a common practice. The reason for this is apparent from this experiment, in which factorial combinations of nitrogen, phosphorus, and potassium have been added to a moribund grass sward established during the reclamation of colliery spoil about four years earlier. There is clearly a gross deficiency of nitrogen, rather than anything else, and this persists even in the second year of treatment. The nitrogen supply in an ecosystem is derived from a capital of organic nitrogen in soil. This experiment, and others, indicates that the size of that capital is crucial in developing ecosystems and that in restoration practice it is essential to devise ways in which it can be built up rapidly (Bloomfield, Handley & Bradshaw, 1982). (Shaded: growth with fertilizer; white: growth without.)

Table 5.3. *The organic soil nitrogen capital needed* (*kg N ha*$^{-1}$) *to satisfy different nitrogen requirements, assuming various decomposition rates* (*Bradshaw*, 1983)

Annual requirement	Decomposition rate 1/64	1/16	1/4	1
200	12800	3200	800	200
100	6400	1600	400	100
50	3200	800	200	50
Type of ecosystem	Montane	Cool temperate	Warm temperate	Tropical

provided do not contain much more than 100 kg N/ha^{-1}, some of which is lost by leaching. So it is clear that the necessary soil capital will take some time to accumulate. This is confirmed by what is found even in well-managed kaolin mine waste reclamation projects in south-western England, where the problem of nitrogen accumulation is reflected not only in the limited amount of total nitrogen accumulated (Marrs, Roberts & Bradshaw, 1980), but also in the low amount mineralized compared with normal soils (Roberts, Marrs & Bradshaw, 1980).

The role of nitrogen in the restoration of self-sustaining ecosystems, as well as in the proper functioning of existing ecosystems, seems almost self-evident from these arguments. But, in fact, lack of appreciation of this role has led to numerous failures in restoration practice. This is matched by the limited discussion that has been devoted to the question of nitrogen supply in relation to the functioning of natural ecosystems. It will be profitable to examine natural ecosystems in the future from the point of view of their nitrogen budgets, an approach exemplified by the recent analysis of tropical montane rainforest by Grubb (1977a), of prairie by Woodmansee (1979), and especially of temperate forests where productivity may be closely related to soil mineral nitrogen supply (Nadelhoffer, Aber & Melilo, 1983). (For further discussion of this point, see Ch. 16.)

In ecosystem restoration there is obviously a need to find ways other than repeated fertilizer applications to provide the nitrogen capital required. An obvious approach is to use legumes and other nitrogen-fixing species such as alder, because these can readily fix more than 100 kg N ha^{-1} yr^{-1} even under difficult conditions. Another, increasingly important technique is the application of various nitrogen-rich wastes such as sewage sludge or the fine fraction from pulverized domestic refuse. In general, the role of nitrogen-fixing species in primary successions has long been recognized. But it is perhaps the evidence of their crucial role in restoration that is refocusing our attention on their importance in natural situations.

The other nutrient that is very likely to be deficient is phosphorus. Some substrates, such as lime wastes and colliery spoils, are not only initially deficient but have high phosphorus sorption capacities (Fitter, 1974). This not only explains why natural ecosystem development can be so slow on these wastes (Bradshaw, 1983), but has also led to raising phosphorus applications to as much as 200 kg/ha^{-1} in the restoration of some materials. Again, though agriculturists have long recognized the crucial role of phosphorus in limiting yield, it is surprising how rarely ecologists have investigated its role in natural systems.

Treating toxicities

The drastic ecological effects of toxicity on degraded or derelict land are demonstrated very clearly by areas contaminated by heavy metals. These can remain nearly bare, colonized only by a sparse vegetation of metal-tolerant plants for periods of time that may be measured in centuries (Ernst, 1974; Bradshaw & McNeilly, 1981). Clearly, attempts to re-establish vegetation in these areas without dealing with the problem of metal toxicity are doomed to failure. (The evolution that has taken place on these sites is itself a fascinating story, summarized by McNeilly in Ch. 18.)

Experiments on these wastes show that plant growth depends on a combination of metal tolerance in the populations of the colonizing species and the presence of sufficient nutrients, especially nitrogen and phosphorus. The ecologically elegant solution for reclamation is therefore to use metal-tolerant plants and to supply fertilizer. This can be very successful (Smith & Bradshaw, 1979). It truly copies nature, but, like nature, it also results in an odd and very simplified ecosystem in which nutrient cycling is so much reduced by the heavy metal toxicity that growth is limited unless repeated fertilizer applications are given (McNeilly, Williams & Christian, 1984). Such sites clearly demonstrate the importance of properly functioning nutrient-cycling systems.

To obtain a normal ecosystem the effects of the metals have to be dealt with completely. A covering of organic matter to bind any available metals was originally thought to be effective. But this effect declines after a few years as the organic matter disappears and the toxicity returns. As a result, the main emphasis has turned to covering toxic substrate layers with an inert layer to serve as a barrier to the upward movement of metals and the downward growth of roots (Williamson, Johnson & Bradshaw, 1982; Smith, 1985).

In the case of metal-contaminated sites, therefore, the nature of the toxicity is such that direct treatment is not completely satisfactory. Once again what is required for successful restoration is indicated by the vegetation colonizing natural, undisturbed metal-contaminated areas. These can be recognized by their anomalous vegetation (Nicholls *et al.*, 1965), even when this vegetation has had many thousands of years in which to develop.

Adding species

In natural ecosystem development, species invade slowly and can take advantage of the developing environment produced by physical and chemical changes that occur during primary succession. They can also take advantage, so to speak, of years when conditions for colonization are especially favorable. Both of these effects are apparent in the natural colonization of kaolin wastes. Nitrogen-accumulating legumes, such as gorse (*Ulex europaeus*), which represent an essential stage in the development of woody species on such sites, themselves colonize only in years when there is a wet spring (Dancer, Handley & Bradshaw, 1977).

In general, the establishment of species by natural processes tends to be slow and stochastic. It also depends on the source of propagules available in the vicinity. So in artificial restoration the required species are introduced artificially and sown by ordinary agricultural or forestry techniques. The choice of species can be tailored to suit the ecosystem being reconstructed, including species suitable for early as well as late stages of ecosystem development; also nitrogen fixers and other appropriate plants, trees, shrubs, and herbs. For practical reasons all the species are usually sown or planted at the same time. This may sound rather simple, but in practice to compress the normal, gradual process of establishment into a single period may actually be difficult.

An important consideration here is the provision of microenvironments for establishment which are suitable, both chemically and physically, for the desired species. There are many ways this might be done. The most common ways are to provide one or more nurse species, and appropriate fertilization. But it can be difficult to know what is appropriate for one particular species, let alone for a whole group of different ones. Some species of *Calluna* and *Erica*, for example, are moorland species normally found in open, very nutrient-deficient habitats. But on kaolin sand wastes, it is found, quite remarkably, that the combination of both a nurse grass and fertilizer leads to the best re-establishment of these two species from dormant seed in a thin scattering of topsoil (Fig. 5.4). The provision of an extra subsoil layer does not have any extra effect. The nurse grass must somehow be providing a suitable microenvironment. The effect of the fertilizer suggests that the early seedling stages are more sensitive to nutritional deficiencies than later stages. Despite its possible competitive effects, the provision of a nurse species in combination with nutrient addition is found to be important for establishment in many situations where ecosystems are being established. This is true even when the aim is to restore faithfully a pre-existing ecosystem, such as coastal heath after mineral sand mining in Australia (Brooks, 1976). In other areas (the Piceance Basin, for example) irrigation may also be valuable (Doerr, Redente & Sievers, 1983). (The importance of

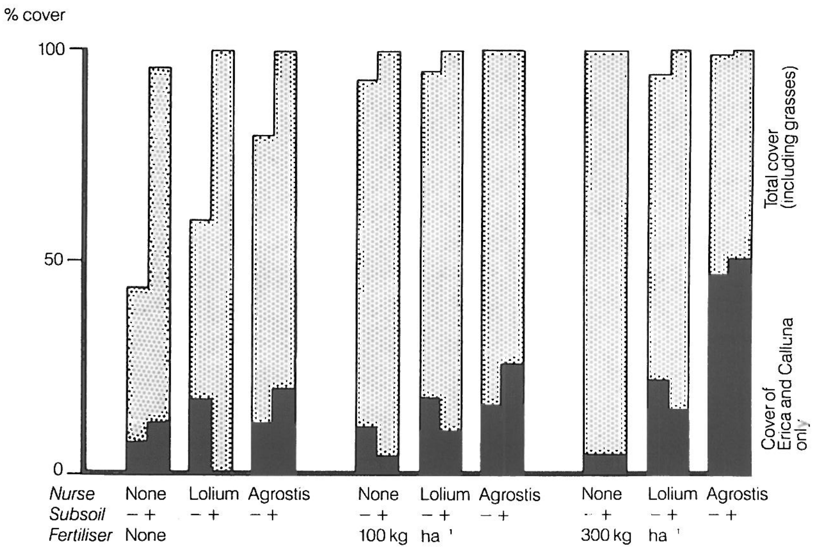

Fig. 5.4. The establishment phase in land restoration is especially important when wild species are being replaced. In this experiment two heathers (*Calluna vulgaris* and *Erica cinerea*) are being established on very sandy kaolin wastes in south-western England by collecting litter from natural heather moorland and spreading it on the waste surface. The effects of a nurse grass (*Agrostis capillaris*), fertilizer, and a thin covering of subsoil are being tested. Despite the fact that the heathers naturally grow in very exposed and nutrient deficient soils, establishment is best after three years on plots treated with a combination of high fertilizer and the nurse grass. Such results not only provide information useful in refining restoration techniques, but also help define more accurately the regeneration niche of the species involved (original data of P. D. Putwain & A. D. Gilham).

appropriate micro-environments for seedling establishment is discussed further by Gross in a subsequent chapter.)

All this suggests that the hard experience of land restoration is beginning to provide good evidence for the interdependence of species in succession. Sequential planting, which is now being found to be useful, will provide further evidence. If tree lupins, for instance, are sown in advance of forest tree planting on degraded sand dunes in New Zealand, tree growth is substantially improved (Gadgil, 1971). The trees are introduced only after the lupins have reached the mature stage, when their nitrogen accumulation has reached a maximum. On kaolin wastes, it is found that if annual grasses and legumes are sown a year ahead of perennial grasses and legumes, the final establishment of the latter is much better. There is still a great deal more practical experience to be gained, however, about species and their establishment in land restoration, and this is likely to have considerable ecological significance.

The contribution of practice to theory

In relation to the maintenance of species richness in plant communities, Grubb (1977b) introduced the concept that the regeneration niche – the particular environment where a plant begins its development – is a very important part of the overall niche. In the restoration of ecosystems one might suppose that the regeneration niche space is wide open. But in reality it may lack particular attributes and therefore be unsuitable for most species. The first ecological step is therefore to manipulate the regeneration niche by physical, chemical, and biological means, to tailor it properly to the species that are wanted. We can do this properly only if we understand the specific requirements of individual species, which, from the evidence of past failures in the establishment phase of ecosystem restoration, it appears we have not always managed to do. These failures can be expensive and may be discouraging, but they do provide opportunities for defining exactly what we do not yet know about the requirements of species and ecosystems. At the same time the general accumulated experience of restoration should make major contributions to general theories of community development.

Succession, for example, is an important ecological concept. Yet the mechanics of succession under various conditions are still widely debated. There are good recent discussions by Connell & Slatyer (1977) and Miles (1979). For our purposes it is best to be very simple. Perhaps the first consideration is our understanding of the origin of the environmental changes that lead to the sort of natural recovery shown in Figure 5.1. This leads to improvement in the environment. Perhaps almost the first point that ecologists discuss is whether these changes are allogenic or autogenic in origin, that is, whether they arise from outside the community (for example, weathering, leaching) or from within it (from plant roots, legumes, etc.). It is clear that in ecosystem restoration both types of factors play important roles.

But the aim of the restorationist is to accelerate succession, and it is clear that these factors are rarely enough by themselves to allow rapid ecosystem development and that considerable artificial help must usually be given. To provide this help, however, it is necessary to understand the factors limiting succession at each point of its progress and to relieve them by cultivation, fertilization, liming, or other specific treatment. There is a need to optimize the environment, both for individual species and for the entire ecosystem. This is because both species and ecosystems have specific physical and chemical requirements, which in natural ecosystem development may be satisfied only after a lapse of time (see Ch. 7).

As a result, ecosystem restoration provides a way of seeing more clearly the needs of ecosystems and the importance of both allogenic and autogenic factors in primary succession. In particular, the contribution of autogenic factors which can be demonstrated in the course of restoration work indicates the importance of *facilitation*, in the sense of Slatyer (1977). This is the idea that one species makes it easier for a second species to participate in a particular succession, an assertion that has at times been questioned (Drury & Nisbet, 1973).

Facilitation leads to "relay floristics", the concept that there is a specific sequence of species (Egler, 1954). One of the most interesting aspects of ecosystem restoration, the significance of which has hardly been explored, is the practical need to compress establishment into one phase so that relay floristics cannot occur. For this reason the results of techniques such as the establishment of trees by seed as part of the initial treatment (Luke, Harvey & Humphries, 1982) will be of great interest. As might be expected, the results have been rather variable so far.

In this discussion little attention has been paid to the influence of competition in restoration practice yet it certainly must occur. Indeed there is evidence that it does occur, an example being the deleterious effects of grass on tree establishment (Bradshaw & Chadwick, 1980). But in general we have not paid enough attention to competition as a critical factor, and it will be discussed in later chapters by Gilpin, Gross, Rosenzweig, and Kline & Howell. If we include predation as part of competition, then we must report almost total ignorance, which, in view of the crucial role of such factors in natural ecosystems, is certainly unsatisfactory.

In conclusion, it is clear that natural succession has many probabilistic components, and that in ecosystem restoration these elements have been, or should be, removed as far as possible. At the same time the whole construction process has to be hastened. This requires us to understand ecosystem needs and functions very precisely and in practical terms. Ecological theory has much to contribute to this practical goal, but at the same time restoration practice has much to contribute to ecological theory by providing not only experimental evidence but also an acid test of our understanding.

Ecologists working in the field of ecosystem restoration are in the construction business and, like their engineering colleagues, can soon discover if their theory is correct by whether the airplane falls out of the sky, the bridge collapses, or the ecosystem fails to flourish.

References

Bloomfield, H. E., Handley, J. F. & Bradshaw, A. D. (1981). Topsoil quality. *Landscape Design*, **135**, 32–4.

Bloomfield, H. E., Handley, J. F. & Bradshaw, A. D. (1982). Nutrient deficiencies and the aftercare of reclaimed derelict land. *Journal of Applied Ecology*, **19**, 151–8.

Bradshaw, A. D. (1983). The reconstruction of ecosystems. *Journal of Applied Ecology*, **20**, 1–17.

Bradshaw, A. D. (1984). Ecological principles and land reclamation practice. *Landscape Planning*, **11**, 35–48.

Bradshaw, A. D. & Chadwick, M. J. (1980). *The Restoration of Land*. Oxford: Blackwell.

Bradshaw, A. D. & McNeilly, T. (1981). *Evolution and Pollution*. London: Arnold.

Brooks, D. R. (1976). Rehabilitation following mineral sand mining on North Stradbrooke Island, Queensland. In *Landscaping and Land Use Planning as Related to Mining Operations*, pp. 93–104. Adelaide: Australasian Institute of Mining and Metallurgy.

Connell, J. H. & Slatyer, R. D. (1977). Mechanisms of succession in natural communities and their role in community stability and organisation. *American Naturalist*, **111**, 1119–44.

Coppin, N. J. & Bradshaw, A. D. (1982). *Quarry Reclamation*. London: Mining Journal Books.

Crocker, R. L. & Major, J. (1955). Soil development in relation to vegetation and surface age at Glacier Bay, Alaska. *Journal of Ecology*, **43**, 427–48.

Dancer, W. S., Handley, J. F. & Bradshaw, A. D. (1977). Nitrogen accumulation in kaolin mining wastes in Cornwall. I. Natural communities. *Plant and Soil*, **48**, 153–67.

Department of Environment (1982). *Bush Farm Working Party, Joint Agricultural Land Experiment Program Report No 2 for Bush Farm, Upminster, Essex.*

Doerr, T. B., Redente, E. F. & Sievers, T. E. (1983). Effect of cultural practices on seeded plant communities on intensively disturbed soils. *Journal of Range Management*, **36**, 423–8.

Drury, W. H. & Nisbet, I. T. (1973). Succession. *Journal of the Arnold Arboretum*, **54**, 331–68.

Egler, F. E. (1954). Vegetation science concepts. I. Initial floristics composition, a factor in old-field development. *Vegetatio*, **4**, 412–17.

Elias, C. O., Morgan, A. L., Palmer, J. P. & Chadwick, M. J. (1982). *The Establishment, Maintenance and Management of Vegetation on Colliery Spoil Sites*. University of York: Derelict Land Research Unit.

Ernst, W. (1974). *Schwermetallvegetation der Erde*. Stuttgart: Fischer.

Fitter, A. H. (1974). A relationship between phosphorus requirements, the immobilisation of added phosphate, and the phosphate buffering capacity of colliery shales. *Journal of Soil Science*, **25**, 41–50.

Fridriksson, S. (1975). *Surtsey*. London: Butterworth.

Gadgil, R. L. (1971). The nutritional role of *Lupinus arboreus* in coastal sand dune forestry. I. The potential influence of undamaged lupin plants on nitrogen uptake by *Pinus radiata*. *Plant Soil*, **34**, 357–67.

Gray, H. (1982). Plant dispersal and colonisation. In *Ecology of Quarries*, ed. B. N. K. Davis, pp. 27–31. Cambridge: Institute of Terrestrial Ecology.

Grubb, P. J. (1977a). Control of forest growth and distribution on wet tropical mountains. *Annual Review of Ecology and Systematics*, **8**, 83–107.

Grubb, P. J. (1977b). The maintenance of species richness in plant communities and the importance of the regeneration niche. *Biological Reviews*, **52**, 107–45.

Hall, I. G. (1957). The ecology of disused pit heaps in England. *Journal of Ecology*, **45**, 689–720.

Harper, J. L. & Benton, R. A. (1966). The behaviour of seeds in soil, part 2. The germination of seeds on the surface of a water supplying substrate. *Journal of Ecology*, **54**, 151–66.

Hoogerkamp, M., Rogaar, H. & Eijsackers, H. F. (1983). The effect of earthworms (Lumbricidae) on grassland on recently reclaimed polder sods in the Netherlands. In *Earthworm Ecology*, ed. J. E. Satchell, pp. 85–104. London: Chapman & Hall.

Jansen, I. J. (1981). Reconstructing soil after surface mining of prime agricultural land. *Mining Engineering*, March 1981, 312–4.

Leisman, G. A. (1957). A vegetation and soil chronosequence on the Mesabi Iron Range spoil banks, Minnesota. *Ecological Monographs*, **27**, 221–45.

Luke, A. G. R., Harvey, H. & Humphries, R. N. (1982). The creation of woody landscapes on roadsides by seeding – a comparison of past approaches in West Germany and the United Kingdom. *Reclamation and Revegetation Research*, **1**, 243–53.

Magnuson, J. J., Regier, H. A., Christien, W. J. & Sonzogi, W. C. (1980). To rehabilitate and restore Great Lakes ecosystems. In *The Recovery Process in Damaged Ecosystems*, ed. J. Cairns, pp. 95–112. Michigan: Ann Arbor Science.

Marrs, R. H. & Bradshaw, A. D. (1982). Nitrogen accumulation, cycling and the reclamation of china clay wastes. *Journal of Environmental Management*, **15**, 139–57.

Marrs, R. H., Roberts, R. D. & Bradshaw, A. D. (1980). Ecosystem development on reclaimed china clay wastes. I. Assessment of vegetation and capture of nutrients. *Journal of Applied Ecology*, **17**, 709–18.

Marrs, R. H., Roberts, R. D., Skeffington, R. A. & Bradshaw, A. D. (1983). Nitrogen and the development of ecosystems. In *Nitrogen as an Ecological Factor*, ed. J. A. Lee, S. McNeill & I. H. Rorinson, pp. 113–36. Oxford: Blackwell.

McNeilly, T., Williams, S. T. & Christian, P. J. (1984). Lead and zinc in a contaminated pasture at Minera, N. Wales and their impact on productivity and organic matter breakdown. *The Science of the Total Environment*, **38**, 183–98.

Miles, J. (1979). *Vegetation Dynamics*. London: Chapman & Hall.
Nadelhoffer, K. J., Aber, J. D. & Melilo, J. M. (1983). Leaf–litter production and soil organic matter dynamics along a nitrogen–availability gradient in Southern Wisconsin (USA). *Canadian Journal of Forestry Research*, 13, 12–21.
Nicholls, O. W., Provan, D. J., Cole, M. M. & Tooms, J. S. (1965). Geobotany and geochemistry in mineral exploration in the Dugald River area, Cloncurry District, Australia. *Transactions of the Institute of Mining and Metallurgy*, 74, 695–799.
Park, D. G. (1982). Seedling demography in quarry habitats. In *Ecology of Quarries*, ed. B. N. K. Davis, pp. 32–4. Cambridge: Institute of Terrestrial Ecology.
Rimmer, D. L. (1982). Soil physical conditions on reclaimed colliery spoil heaps. *Journal of Soil Science*, 33, 567–79.
Roberts, R. D. & Bradshaw, A. D. (1985). The development of a hydraulic seeding technique for unstable sand slopes. II. Field evaluation. *Journal of Applied Ecology*, 22, 979–94.
Roberts, R. D., Marrs, R. H. & Bradshaw, A. D. (1980). Ecosystem development on reclaimed china clay wastes. II. Nutrient compartmentation and nitrogen mineralization. *Journal of Applied Ecology*, 17, 719–26.
Roberts, R. D., Marrs, R. H., Skeffington, R. A. & Bradshaw, A. D. (1981). Ecosystem development on naturally colonized china clay wastes. I. Vegetation changes and overall accumulation of organic matter and nutrients. *Journal of Ecology*, 69, 153–61.
Schaller, F. W. & Sutton, P. (eds) (1978). *Reclamation of Drastically Disturbed Lands*. Madison: American Society of Agronomy.
Slatyer, R. D. (ed.) (1977). *Dynamic Changes in Terrestrial Ecosystems: Patterns of Change, Techniques for Study and Application to Management*. Paris: UNESCO.
Smith, M. A. (ed.) (1985). *Contaminated Land: Reclamation and Treatment*. New York: Plenum.
Smith, R. A. H. & Bradshaw, A. D. (1979). The use of metal tolerant plant populations for the reclamation of metalliferous wastes. *Journal of Applied Ecology*, 16, 595–612.
Williamson, N. A., Johnson, M. S. & Bradshaw, A. D. (1982). *Mine Wastes Reclamation*. London: Mining Journal Books.
Woodmansee, R. G. (1979). Factors influencing input and output of nitrogen in grasslands. In *Perspectives in Grassland Ecology*, ed. N. French, pp. 117–34. New York: Springer.

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6

Prairies

Prairie restorations were among the first plant community restorations attempted (Sperry, 1983), and prairie continues to be a community of special interest to restorationists, at least partly because prairies lend themselves to experiments carried out on a small scale, over a reasonable length of time, and even using many conventional agricultural techniques (see Ch. 3). Prairies are planted for different purposes, however, and projects vary greatly in scale. At one extreme are the relatively small, simplified, stylized natural landscapes used in residential and industrial sites to create an esthetic statement of the "visual essence" of native prairies (Morrison, 1975, 1979; Diekelmann & Schuster, 1982); at another are complete community restorations, such as Curtis and Greene Prairies at the University of Wisconsin-Madison Arboretum (Ch. 17), in which the goal is to establish the structure, species composition and interactions characteristic of a functioning prairie ecosystem. Prairie plantings are also used in parks and along roadsides to achieve a relatively open view and provide a variety of color, texture and form, and at the same time minimize maintenance costs (Morrison, 1981); and on sanitary landfills and mine tailings to reduce erosion and provide cover for wildlife.

Prairies are biological communities dominated by grasses and having less