THE ROLES OF BIOTIC AND ABIOTIC DIVERSITY IN ESTABLISHING ECOSYSTEM INTEGRITY ON RECLAIMED MINELANDS, AND STRATEGIES FOR THEIR ENHANCEMENT[1]

Keith Winterhalder[2]

Abstract. By definition, ecosystem integrity presupposes biotic diversity, and biotic diversity is likely to be at its greatest when the environment is itself diverse. Under certain circumstances, as in some smelter-affected areas, the mineland to be reclaimed is a degraded natural landscape. In such a case, the physical diversity of the site, in combination with minimal amelioration such as liming and/or fertilization where necessary, will lead to differential plant establishment and success, and to a vegetational mosaic rather than a homogenous near-monoculture. The biodiversity will continue to increase as the site is colonized by native species. In the case of a more homogenous mineland such as a tailings deposit, it is desirable to create a physical and chemical mosaic on the site by means of such strategies as differential liming and fertilization, varying the types and depths of covering materials, and microtopographic manipulation. In the case of covering materials, a discontinuous cover is advantageous, because of the edge effect that is created. In both types of mineland, the biological diversity can be enhanced directly by introducing ”islands” of forest topsoil, and “plugs” of native forest soil containing understory herbs characteristic of the ecozone, as well as appropriate tree and shrub seedlings.

Introduction

The restoration of biodiversity on a degraded natural landscape and on a mine waste deposit present two very different challenges, because in the former the site already contains some physical diversity, whereas the mine waste is more likely to be homogeneous.

Abiotic Diversity on Degraded Natural Landscapes

Sudbury, Ontario, Canada provides an appropriate case study for the degraded natural landscape scenario (Winterhalder 1994, 1995a-c). The foundation of the natural landscape consists of

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[2]Laurentian University & Wintergreen Ecological Services Sudbury, Ontario, Canada

extensive outcrops of Precambrian rock with pockets of glacial till, forming a mosaic with lowland deposits of alluvium and sandy outwash plains. The landscape already shows pattern of spatial and environmental diversity at a number of different scales, with the pollution zones superimposed on the natural landscape (Winterhalder 1988). The hillsides originally supported extensive stands of red pine (*Pinus resinosa*) and white pine (*Pinus strobus*). One hundred years of logging, fire, soil erosion and enhanced frost action, as well as sulphur dioxide fumigation and copper, nickel and iron particulate fallout from the region's three smelters, resulted in the creation of a zone of barren land around each smelter, covering a total of 10,000 hectares. The barren soils on the slopes have a stony covering that is the result of the combined action of frost-heaving and erosion on the glacial till-derived soil. They also show a pattern of decreasing pH and increasing copper and nickel content as the three smelters are approached, and are phytotoxic to all but the metal-tolerant ecotypes of tufted hairgrass (*Deschampsia caespitosa)*, tickle grass (*Agrostis scabra*) and dwarf birch (*Betula pumila*). The barrens are surrounded by a 36,000 hectare zone of stunted, semi-barren woodland, characterized by patches of bare soil between the relict, coppiced white birch (*Betula papyrifera*), red maple (*Acer rubrum*) and red oak (*Quercus borealis*). Occasional relict individuals of these three woody species also occur on some of the barren areas.

The reclamation technique employed was the manual surface application of ground dolomitic limestone, a low-N, high-P fertilizer and a grass-legume seed mixture. (redtop (*Agrostis gigantea*), timothy (*Phleum pratense*), Canada bluegrass (*Poa compressa*), Kentucky bluegrass (*Poa pratensis*), creeping red fescue (*Festuca rubra*), Alsike clover (*Trifolium hybridum*) and birdsfoot trefoil (*Lotus corniculatus*)). The open grassy sward that results is conducive to colonization, since it offers numerous openings and microhabitats for volunteer seedlings. It was found that, once the phytotoxicity of the soil is suppressed by liming, wind-dispersed trembling aspen (*Populus tremuloides*), white birch and willows (*Salix* spp.) begin to colonize. Figures 1 & 2 give an indication of the diversity of microenvironments available in the barren landscape, and of the vegetation mosaic that results following treatment, despite the fact that the treatments (liming, and seeding) were homogeneously applied.

Figure 1. Barren landscape near Sudbury, Ontario in 1983, showing topography and wealth of microhabitats.

Figure 2. The same landscape in 1989, three years following treatment, showing mosaic of vegetation.

The approach taken in Sudbury can be thought of as minimal amelioration or minimal intervention (Skaller 1981), since the limestone application rarely raises the soil pH by more than one unit and neither limestone nor fertilizer treatment is repeated after the first application. Another way of looking at limestone application is as a "trigger factor", since it removes the primary limiting factor to colonization, and allows natural succession to proceed. Hedin (1992) refers to this phenomenon as the "elimination of a colonization bottleneck". An advantage of minimal amelioration with respect to biodiversity is the fact that the site does not become swamped with weed species, as it would be if the soil were heavily fertilized or if topsoil were used. This gives native species a better opportunity to colonize. Furthermore, when limestone is applied manually, it is inevitable that it will be distributed in a patchy fashion, so to some extent a mosaic ensues, in which the degree of liming varies from zero to optimal or even excessive. The liming mosaic is itself superimposed on a mosaic of soil characteristics resulting from the differential erosion of the original O and A horizons of the soil. This is beneficial, since it leads to a more random spacing of plants than an even cover would, as well as creating an environmental mosaic that will favor diversity both in terms of species and genetic biotypes.

Some preliminary studies have indicated that a certain amount of selection of species with respect to pH has already occurred at the Sudbury site. When soils supporting specific species are individually sampled, a clear pattern emerges on the treated land, in which the soil under birch is only marginally less acid than that under the acid-tolerant *Pohlia* moss, while the native pearly everlasting (*Anaphalis margaritacea*) and the two seeded legumes are associated with a much less acid soil (Figure 3).

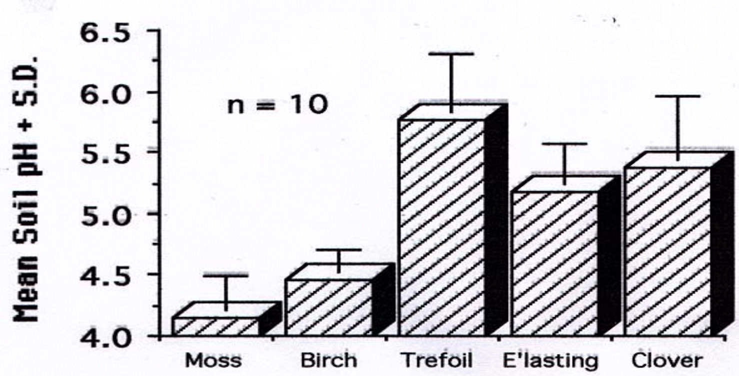

Figure 3. Distribution of plant species cover in relation to soil pH, 12 years after treatment.

To some extent, this pattern may indicate the pH "preferences" of the plant species, since the soil is itself patterned with respect to pH as a result of the liming technique. However, competition is also an important factor in species distribution, and the birch is probably occupying the available niches that are not necessarily optimal, but are too acid for the other species, and are within its own range of tolerance. The manual method of limestone application ensures a mosaic of soil pH and base content, and the resultant environmental mosaic makes for both floristic and genetic diversity, especially with respect to metal tolerance. On the other hand, a homogeneous, rich application of limestone and fertilizer might result in the loss of metal-tolerant races of grasses through competition.

At the same time, the plants may themselves be influencing the soil pH through base depletion or base enrichment. The pH of a soil is, to a great extent, a function of its base status. In the short term, this fact explains the effectiveness of limestone as a trigger factor in initiating detoxification and plant growth. In the longer term, it might be expected that the neutralizing power of the limestone would be "used up", leading to regression of the plant community. In fact, however, the detoxification of the soil allows for the penetration of roots into a larger volume of soil and the movement of calcium and magnesium to the soil surface, and this initiation of movement of bases and other minerals to the soil surface, Aber's (1987) “cation pump”, is an important component of the Sudbury landscape's recovery process. Indeed, it is likely that an initial decline in pH following liming is followed by a rise as bases are brought to the surface from the subsoil and deposited in leaf litter.

Another random variable that influences vegetation pattern and diversity is that of the interaction between the time of amelioration and other environmental variables. The synchronization of a good seed year, the presence of a recently-treated area with a bare stony surface or an open grass cover, and moist weather and suitable winds during the short period of seed dispersal and seed viability, is especially important to the establishment of aspen in the Sudbury area, and may explain some of the patchiness of its distribution. Leisman (1957) has made a similar point with respect to the establishment of trembling aspen and balsam poplar *(P. balsamifera)* on iron range spoil banks in Minnesota, and also points out that aspens only produce good seed crops every four or five years, while Dancer *et al.* (1977) showed that gorse *(Ulex europaeus)* only colonized kaolin wastes in Cornwall in years when there was a moist spring and early summer.

In summary, then, minimal amelioration enhances biodiversity because of the range of microsites that are formed by the interaction of natural topography, the physical and chemical properties of the soil following erosion, and the timing and the uneven surface application of limestone. Thus, following revegetation treatment, another layer of patterning, both spatial and temporal, is superimposed on the already highly patterned landscape.

Abiotic Diversity on Mine Wastes

Mine tailings present a difficult substrate for revegetation, especially if they are pyritic and acid-generating, and the usual approach taken is to attempt the establishment of a relatively homogeneous cover of grasses and legumes. As a consequence, revegetated mine sites often exhibit a much lower alpha (i.e. within-habitat or within-community) biodiversity than unmined sites, due to the homogenizing impact of the cultural practices (Krabbenhoft et al. 1985). The plant cover may show a response to the fact that the tailings surface itself is not entirely homogeneous (e.g. Crowder *et al*. 1982, McLaughlin and Crowder 1988), but differences are often subtle, or consist solely of a vegetated/ unvegetated pattern. Nevertheless, wherever possible a random or planned diversity should be introduced into as many as possible of the mining and reclamation practices (e.g. waste deposition, site preparation, growth medium amelioration, plant species used and method of plant establishment), ways should be devised of sustaining and enhancing any diversity already present in the newly revegetated system.

In most cases of mine waste deposits such as tailings, it may be necessary to diversify the environment in order to engender a degree of biological diversity during the revegetation process. This can be done in a number of ways, including the use of limestone, fertilizers and other ameliorants, or cover materials such as topsoil or gravel, preferably laid down in the form of a mosaic or in strips. Not only does the creation of a mosaic or strips of materials with different physical and chemical characteristics give a diversity of environment, but it also increase the amount of edge. Figures 4 and 5 show the edge effect created by placing a papermill sludge cover on acid-generating tailings and metal-phytotoxic soil, respectively. Furthermore, the enhanced edge may form a refugium and centre of dispersal for soil fauna (Nentwig, 1988).

Figure 4. Trembling aspen and willow seedlings colonizing the edge of a papermill sludge cover plot on copper tailings, Pronto Mine, Ontario.

A soil that is uniformly fertile will tend to encourage opportunist, weedy species, and is unlikely to lead to a diverse collection of native species, at least in the short term. The most direct way of creating nutritional diversity in a growth medium is to vary the application of fertilizer or other sources of nutrients (e.g. topsoil, compost etc.), or, as described above, to use covering layers.

An indirect approach to differential soil nutrient enhancement involves the planting of plant species that themselves alter the nutritional status of the soil. The most obvious example would be the use of a nitrogen fixer. There are numerous reports of *Robinia pseudo-acacia* (black locust) providing a favourable environment for colonization by other woody species, e.g. Ashby *et al.* (1980) in Indiana, Missouri and Kansas. It is sometimes possible to vary microtopography and soil nutrient status simultaneously. For example, the microtopography of a peaty, copper/zinc-contaminated area at the Kam-Kotia mine, Timmins, Ontario, has been manipulated at the experimental level by the creation of small mounds of gravelly sand, approximately 1 m in width and 20 cm in height. These mounds have been limed, lightly fertilized, and seeded with a grass-legume mix. Within two years, the sparse grass cover has trapped seeds of white birch from the native seed rain, and the mounds are dominated by healthy birch seedlings.

Figure 5. Birch seedlings colonizing the edge of a papermill sludge cover plot on acid, copper and nickel-contaminated soil, Falconbridge, Ontario.

<u>Direct Enhancement of Biotic Diversity</u>

<u>Seeding as a source of diversity</u>

A number of direct-seeding techniques have been suggested for the enhancement of biodiversity in revegetation, including the use of a "double-drilling" technique, in which seeds of species with different characteristics are placed in different compartments of the seedbox of a drill seeder (Long

1985). Alternatively, one can seed shrubs in strips, and alternate them with strips of grasses (Richardson & Trussell 1981), or grass and shrub seeds can be combined and seeded with a Brillion seeder (Richardson et al. 1986).

Topsoil islands and native soil plugs as a diversification strategy

One method of decreasing the limiting nature of the seed rain on a grassed tailings deposit is to create islands of topsoil from mature forest communities. Glass (1989), in his review of the role of seed banks in restoration and management, points out that the seed bank in a plant community often shows a lack of close correspondence to the above-ground vegetation, and may contain species from earlier stages in succession. The introduction of soil from a plant community that is the climax for the area is therefore advisable, even if it is only feasible to use a small amount as a seed source and microbial inoculum. The hope is that the propagules in the topsoil will germinate or sprout, and that at least some of them will survive. The richer forest soils will probably be invaded with weeds, but this is unlikely to be a problem in the case of low-nutrient or acid soils. An alternative approach is to transplant plugs consisting of plants and the soil in which they are growing from natural communities, so that the plants can act as a seed source. The use of plugs also introduces a small seed bank. This approach has the advantage that large volumes of soil are not moved, and that individual species can be selected for transplanting.

Both approaches have the advantage that soil microflora and fauna are moved along with the topsoil or plugs. Soil fauna play an important role in litter decomposition and nutrient cycling (Glass 1989), and they may become critical elements in the reestablishment of a functioning ecosystem on mined land. In the acid, metal-contaminated soils of the Sudbury region, Behan-Pelletier & Winterhalder found only three oribatid mite species on barren soils, but this increased to thirteen species a few years following revegetation. Semi-barren soils, with intermediate pH and copper and nickel levels, supported thirty-three species of oribatid, but still far fewer than in undisturbed Ontario forests. Although the fauna of the semi-barren communities that surround the barrens form a source of immigrant mites for the revegetated barrens, there would be some benefit in using the topsoil island or plug approach as an additional source both of soil fauna and soil microflora.

Genetic diversity as an aspect of biodiversity

Plant populations are not homogeneous entities, and genetic diversity is just as important as species diversity on a reclamation site. Wide genetic diversity will enable the species to inhabit a larger number of microsites, to adapt more readily to environmental changes, and may lead to recombination and the formation of genotypes that are better suited to the degraded habitat than any of the parents. If possible, plants of local provenance and similar environments should be used for transplanting or seed sources, but the number of parents should be as high as possible, especially if genetic variability within the stand is suspected of being large. Millar & Libby (1989) go so far as to suggest that, if no local native stock of a desired species are available, a new "landrace" can be built from a mixture of promising distant populations. Handel *et al.* (1994) have also suggested the use of mixtures of stock plants to introduce genetic diversity into a restoration site.

On the other hand, it may sometimes be appropriate to choose very specific ecotypes from natural sites that closely resemble the restoration site, but may be quite isolated geographically. A similar approach to diversification on unusual industrially-created substrates was taken by Ash *et al.* (1994), who established plant species from alkaline grassland on alkaline chemical waste and blast furnace slag, and species from acidic heathland on colliery shale, all in the U.K.. Introduction techniques included direct seeding of wild species, transplanting young individuals from natural sites or nursery-grown stock, applying 10 mm layers of litter from natural sites, and transplanting small turves. On pulverized fuel ash, the species that the authors were able to establish had no obvious characteristics in common. Seeding was found to be the most effective method of introduction, but the humid British climate might have been a significant factor here.

While it is often suggested, e.g. Handel *et al.* (1994), that direct seeding is the approach that is likely to introduce the most genetic diversity, at a site where establishment rates for direct seeding are extremely low it may be better to transplant a number of individuals, preferably from a variety of sites. This way, there will be an opportunity for recombination and, assuming that the transplants survive for several seasons, there will be more than one opportunity for the plants to become established from seed. It is advisable to establish a fairly large population of each species, to facilitate the progress of natural evolutionary processes (Frankel & Soulé 1981), and plants should be consciously collected from a variety of microsites, or at least in a random fashion. Even collecting a diversity of obvious phenotypes can be helpful.

Conclusions

It is clear that the best strategy in engendering biodiversity and establishing ecosystem integrity is to diversify both the organisms and their physical environment. With respect to abiotic diversification, this can be achieved by varying the topography and soil characteristics of the landscape where this is possible from an engineering and cost point of view. In the case of direct biodiversity enhancement, it should, as far as possible, be both at the species and the genotype level. While there is merit in ensuring that the provenance of the biota introduced are appropriate to the region, it is probably advisable to use plant material from a broader geographic range, in view of the rapid climate change currently occurring. It is also important to maintain corridors between the restored site and the surrounding landscape, to allow free gene flow. Handel et al. (1994) use the phrase "attracting gene flow" to describe this phenomenon.

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