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Dynamics of Plant Communities and Soils in Revegetated Ecosystems: A Sudbury Case Study

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Trigger Factor Effect

Colonization of the Sudbury barrens by metal-intolerant plants is inhibited by metal toxicity under highly acidic conditions, exacerbated by enhanced frost action (see Chapter 7). It was once believed that revegetation of the barren soils would only be achieved if they were deeply tilled, bringing the less-contaminated soil to the surface, but Winterhalder (1974) observed that disturbance or minimal treatment of contaminated soils in the Sudbury area with limestone or fertilizer led to rapid colonization by tickle grass (*Agrostis scabra*). Later, it was found that a thin surface sprinkling of ground limestone would lead to establishment of woody plants such as white birch (*Betula papyrifera*), trembling aspen (*Populus tremuloides*), and willows (*Salix* spp.) (Fig. 13.1). Because this "minimal amelioration" (Skaller 1981) appeared to initiate spontaneous colonization by metal-intolerant plants from a local seed source, it was referred to as a "trigger factor" (Winterhalder 1983).

This simple approach works for several reasons. The stony mantle that covers the eroded, glacial till-derived soils of the slopes traps limestone particles and seeds. Detoxification of the surface allows the development of a deep root system, affording greater stability to the seedling and protecting it against drought and frost-heaving. Ultimately, the insulating effect of leaf litter also contributes to the reduction in frost activity.

Limestone Detoxification of Sudbury Soils

The detoxifying effect of limestone on Sudbury's acidic metal-contaminated soils is the net result of several mechanisms:

1. precipitation of copper and nickel from solution if a sufficiently high pH is achieved
2. reduction in the toxicity of aluminum ions as they combine with hydroxyl ions
3. enhanced plasma membrane integrity in the cells of the root hairs, improving the plant's ability to selectively exclude toxic ions
4. reducing metal ion uptake by mass action effect of calcium and magnesium on the root hairs' exchange complex
5. increased availability of soil phosphorus, which acts as a plant nutrient as well as a partial protection against aluminum toxicity

FIGURE 13.1. Colonization by birch seedlings of a 1-m^2 plot in a semibarren birch woodland near Falconbridge, photographed on August 10, 1985. The acid- and metal-tolerant moss *Pohlia nutans* had been sprinkled with a light covering of ground dolomitic limestone on September 22, 1979.

pH and Base Dynamics on Limed Soil

Limestone treatments normally increase soil pH by between one and two units. For example, at the site shown in Figure 13.2, the unlimed land dominated by metal-tolerant tufted hairgrass (*Deschampsia caespitosa*) has a soil pH of approximately 4.0, whereas the adjacent limed land supporting a lush growth of grasses, forbs, and woody plants has a pH of approximately 6.0.

Manual methods of limestone application ensure a mosaic of soil pH and base content, engendering both floristic and genetic diversity in the colonizing species, especially with respect to metal tolerance. A decade after liming, a clear correlation exists between soil pH and the species that it supports. The soil under birch and the acid-tolerant moss is in the pH 4.0–5.0 range, whereas pearly everlasting (*Anaphalis margaritacea*, a native wildflower) and the two seeded legumes (Alsike clover [*Trifolium hybridum*] and birdsfoot trefoil [*Lotus corniculatus*]) are associated with soil in the pH

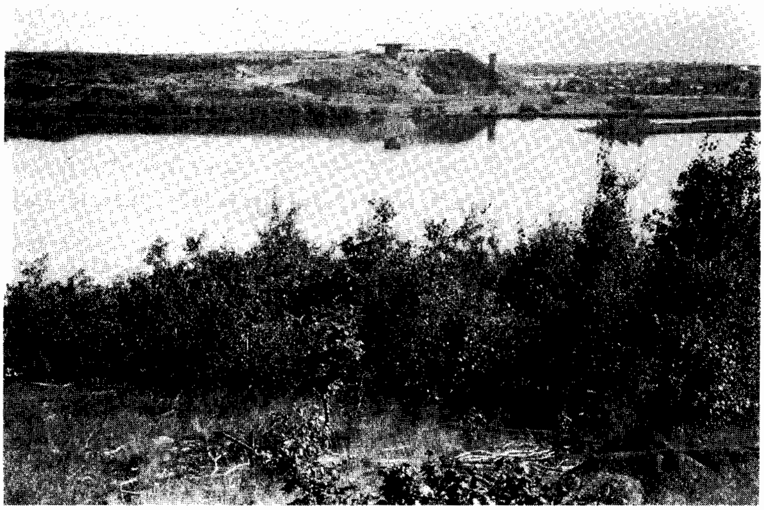

FIGURE 13.2. Treated-untreated boundary south of Copper Cliff in July 1992, showing tufted hairgrass (*Deschampsia caespitosa*) in the untreated foreground and a lush growth of woody plants in the background, which was limed, fertilized, and seeded 10 years previously.

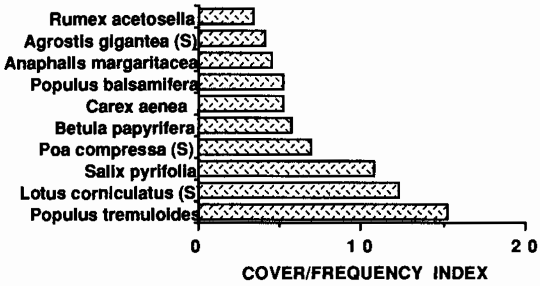

FIGURE 13.3. Ten highest-ranking species on revegetated Sudbury barrens. Species marked with (S) were seeded; others are volunteers. The species are ranked by mean Cover/Frequency Index (Relative Cover + Relative Frequency/2) and based on 1684 quadrats (1 m^2) in 45 transects on land treated 10–14 years previously.

5.0–6.0 range. Calcium and magnesium concentrations (the fraction extractable with dilute acid) show a pattern similar to that for pH, with moss and birch associated with low base cation concentrations and trefoil and clover with high values, pearly everlasting being intermediate. Although these patterns may partially indicate the "preferences" of particular plant species, competition is also an important factor in species distribution. For example, the birch is probably occupying available niches that are not necessarily optimal but are too acid for the other species.

The plants may themselves influence the soil chemistry. Although it might be expected that the neutralizing power of the applied limestone will become exhausted, leading to regression of the plant community, the detoxification of the surface allows for the penetration of roots into a larger volume of soil and facilitates the movement of calcium and magnesium to the surface. This mechanism of soil-base enrichment has been referred to as a "cation pump" by Aber (1987), who pointed out that some tree species are better cation pumps than others, with poplars and spruces being some of the best for base enrichment. However, not all trees produce this effect. The leaf litter from some trees such as pines actually acidifies the forest floor. The current procedure in the Sudbury area, of establishing a vigorous growth of birch and poplar before or concurrently with the planting of pines, therefore seems to be the correct choice.

It has been suggested that as copper and nickel toxicity decreases, calcium and magnesium (as well as phosphorus and nitrogen) might become limiting to plant growth (Lozano and Morrison 1981). Clearly the calcium in the liming material confers plant nutritional benefits, but preliminary experiments have indicated that dolomitic limestone (calcium magnesium carbonate) is more effective than calcitic limestone (calcium carbonate) as a soil ameliorant in certain sites, and it is likely that high calcium levels in soils limed with calcitic limestone can actually induce magnesium deficiency in plants. The possible antagonistic or protective effect of magnesium with respect to nickel toxicity is also under investigation.

Changes in Species Composition after Treatment

In general, a mixture of seeded and volunteer species dominates a site 10 years or so after it has been treated (Fig. 13.3). The principal colonists of amended Sudbury barrens are wind-dispersed, and although there is a small persistent seed bank of tickle grass and white birch, most of the seed source is from the seed rain, which differs from site to site. Figure 13.4 shows an area west of the abandoned smelter at Coniston that was previously barren except for relict white birch and red oak, its grass-legume sward dominated by redtop (*Agrostis gigantea*) 1 year after treatment. Six years later, the grassed area was extensively colonized by white birch. Figure 13.5 shows another barren site, south of the Copper Cliff smelter. Six years after liming and grassing, the dominant woody colonist was trembling aspen.

Plant colonization processes on treated land differ qualitatively as well as quantitatively from natural processes on untreated lands (see Fig. 13.2). In general, the relative importance

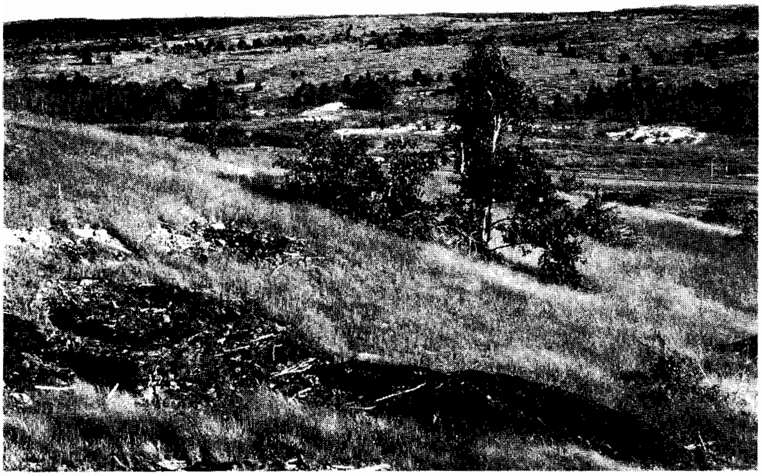

FIGURE 13.4. (*Upper photo*) Grassed site near the abandoned Coniston smelter in 1980 (seeded 1979), showing grass cover dominated by redtop (*Agrostis gigantea*) and scattered "relict" white birch and red oak. (*Lower photo*) The same site in 1986, showing colonization of grassed area by white birch.

of metal-tolerant species is likely to be lower in areas that have been treated. For example, at sites where natural colonization by white birch is occurring, liming allows for the establishment of trembling aspen, but there is no indication that birch growth is also stimulated (Fig. 13.6). In this case, liming has provided a competitive advantage to aspen.

Over the years that follow treatment, the importance of introduced species may rise for a period (see the example of nitrogen-fixing birdsfoot trefoil), but there is a general tendency for introduced species to decrease and for native species to increase (Fig. 13.7). Regardless of treatment differences (e.g., seed mixture, fertilizer, and limestone type and level) at seeded sites, it appears that once the "trigger factor" is applied, other natural forces take over, and a very similar colonization process occurs. However, there are striking differences between sites that have been seeded with the grass-legume mixture and those that are unseeded, with as many as 10 to 20 times fewer woody plant individuals colonizing seeded sites (per unit area).

Because the application of limestone alone is sufficient to initiate plant growth, one could argue that seed and fertilizer application is superfluous, wasteful of resources, and ecologically inappropriate. Seeding does assist in

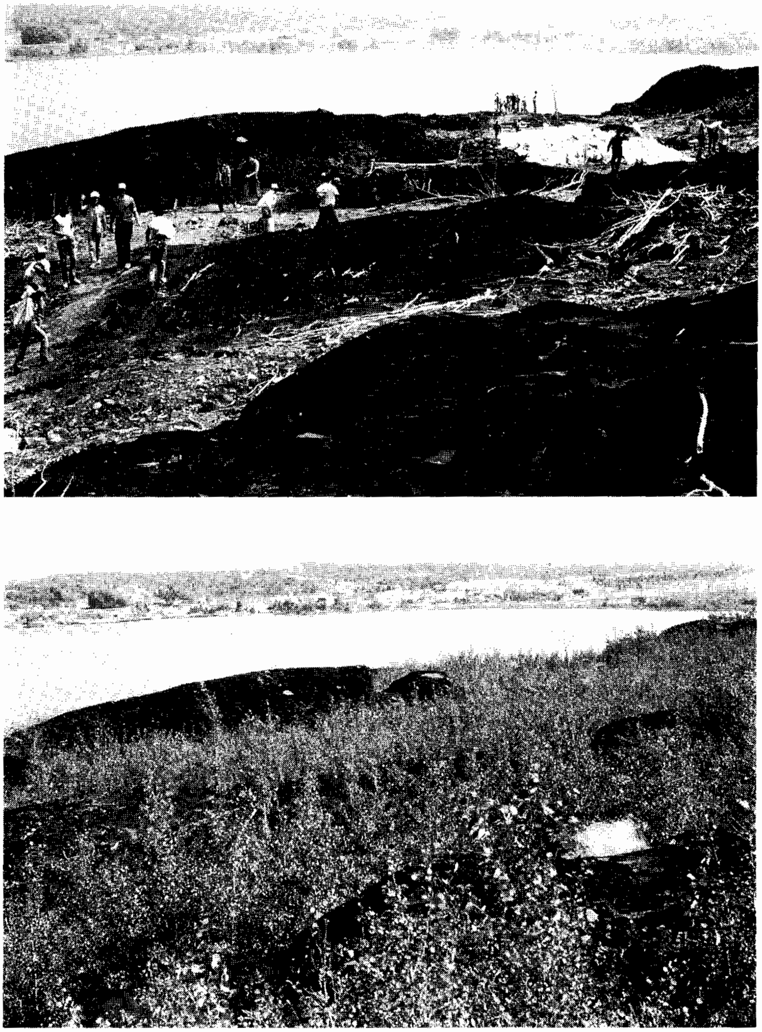

FIGURE 13.5. (*Upper photo*) North shore of Kelly Lake near the Copper Cliff smelter during the liming procedure in 1983. (*Lower photo*) The same site in 1989, showing colonization of grassed land by trembling aspen.

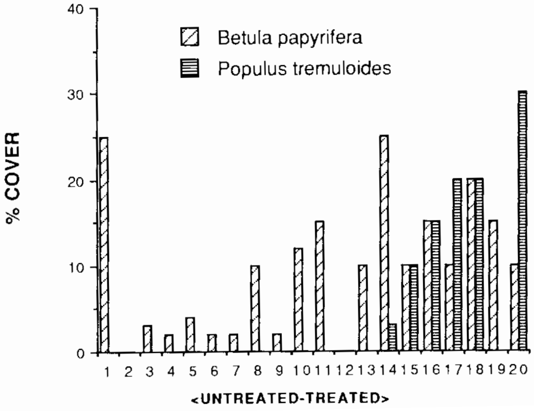

FIGURE 13.6. Percentage cover of white birch (*Betula papyrifera*) and trembling aspen (*Populus tremuloides*) across a liming boundary 14 years after treatment.

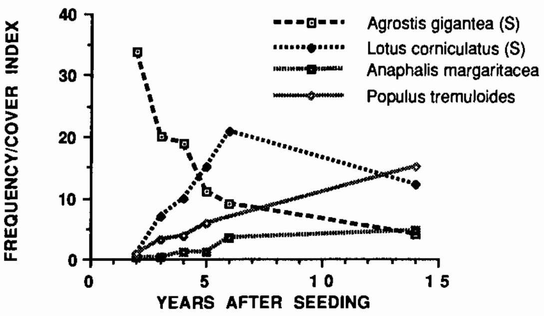

Figure 13.7. Change in relative importance of four plant species over the first 14 years after treatment. S, seeded.

rapidly achieving the aesthetic goals of "regreening" (Chapter 8) and contributes to soil stabilization, microclimate amelioration, and nitrogen fixation, but the agronomic cover also seems to have another beneficial effect. Unseeded areas develop a dense thicket of birch, poplar, and willow undergoing vigorous competition, whereas the woody plants in seeded areas colonize in an open random fashion, leading to good spatial and structural diversity in the stand.

Seeding or planting and natural colonization or "succession" are by no means mutually exclusive, because the seeded or planted vegetation acts as a "nurse crop" to the colonists. Like the pioneer species that initiate natural succession, a nurse crop facilitates colonization by enhancing the microenvironment, reducing evapotranspiration and increasing snow cover. It also plays a critical role in trapping windblown seeds. However, competition, usually from grasses, can form a barrier to colonization and succession on many reclamation sites, as well as competing with planted trees for light and nutrients (Bradshaw and Chadwick 1980) and forming a winter habitat for bark-gnawing rodents. However, in the Sudbury land reclamation program, the use of low seed and fertilizer rates, probably assisted by the stony soil, seems to have eliminated the competition factor.

Native Transplants as a Form of Nucleation

In their study of the Grand Bend sand dunes on Lake Huron, Yarranton and Morrison (1974) noticed that individuals of certain pioneer species such as red cedar (*Juniperus virginiana*) formed nuclei for the initiation of patches of other "persistent" species that spread and eventually coalesced. Miller (1978) suggested that such an approach might be taken in revegetation, in that selected "pioneer" species could be planted in clumps, then the persistent species introduced into the clumps once the pioneers are well established.

A modification of this approach is under investigation on the revegetated Sudbury barrens as a means of introducing understory species characteristic of the targeted plant community. When native species are transplanted from their natural environment in blocks of their own soil, seedlings or propagules of associated species are inevitably introduced with them. For example, species introduced incidentally during the transplantation of soapberry (*Shepherdia canadensis*) and bearberry (*Arctostaphylos uva-ursi*) include common juniper (*Juniperus communis*), white spruce (*Picea glauca*), wild strawberry (*Fragaria virginiana*), wild basil (*Satureja vulgaris*), balsam ragwort (*Senecio pauperculus*), starry false solomon's seal (*Smilacina stellata*), wood-lily (*Lilium philadelphicum*), yellow lady-slipper (*Cypripedium calceolus*), and several species of asters (*Aster* spp.) and goldenrods (*Solidago* spp.). This procedure is likely to be equally beneficial with respect to the introduction of appropriate soil microorganisms.

Acceleration of Succession

The restoration ecologist can test the various hypotheses that attempt to explain succession by the appropriate use of manipulation (Harper 1987). For example, an attempt can be made to "bypass" some of the normal seral stages by soil amelioration (simulating the effects of the previous seral stage according to the relay floristics hypothesis) or by planting species that are usually "later colonists" or have a poor dispersal mechanism. The latter approach is taken in Sudbury's land reclamation program, where the three native pines (jack, red, and white) do not colonize immediately in the absence of a suitable seed bed but are planted on treated land within the first few years after treatment (Beckett and Negusanti 1990). They are planted in small groups to avoid the appearance of a plantation, and it is hoped that they will form a seed source for future colonization.

Although the goal of the revegetation process in Sudbury is a stable, functioning, quasi-natural biotic community (i.e., one that has as large a component as possible of species and biotypes that have evolved under the regional environment), a biotic community identical to the "natural" one may be neither possible nor desirable as an endpoint. Not only is there no uniquely natural association of species in the region, but ecological concepts such as "association" and "climax" are, to quote Whittaker (1977) "abstractions; . . . essentially human creations serving to order, interrelate, and interpret some of the information about natural communities available to us."

Nutrient Cycling and the Potential for Nutrient Limitations

Phosphorus

The phosphorus "working capital" in a soil or in a soil parent material can limit the type of plant community that will ultimately occupy the site (Beadle and Burges 1949). In the short term, however, phosphorus limitation in the Sudbury area has only been shown on some sandy soils, where phosphorus deficiency becomes a secondary limiting factor once metal toxicity is eliminated. Nevertheless, when such sites were limed, fertilized, and sown to Canada bluegrass (*Poa compressa*) in 1974, 20 years later they were able to support clonal patches of trembling aspen and sweet fern (*Comptonia peregrina*), as well as jack pine (*Pinus banksiana*) and red pine (*P. resinosa*) plantations, suggesting that once plants are able to explore the deeper soil, the necessary phosphorus becomes available.

On the stony slopes, the reservoir of phosphorus present in the residual organic matter is sufficient to support plant growth for several years, depending on the degree of erosion that has occurred. Furthermore, limestone application has a beneficial effect in making phosphorus in acid soils available to plants, both through the release of phosphate from inorganic complexation (Brady 1974) and through the enhanced mineralization of organic matter (Fransen 1991). Furthermore, there is also a small reservoir of phosphorus in the unweathered glacial till pebbles that characterize these soils, and the activities of vesicular-arbuscular mycorrhizae, which aid in phosphorus nutrition (Chapter 16), are also stimulated by liming (Blundon 1976).

Plant and soil analysis indicate that a significant buildup of phosphorus has occurred in the revegetated system. The largest buildup is in the aboveground biomass, but with some increase also in root systems and soil. Species play distinct roles in the phosphorus cycle. For example, in Alsike clover, most of the phosphorus is located in the soil and the plant roots, whereas phosphorus buildup in birch is mainly in the shoot system, with a smaller buildup in soil phosphorus.

Nitrogen

Nitrogen deficiency is often the dominant limiting factor in land reclamation (Bradshaw and Chadwick 1980), but on the Sudbury barrens, the residual organic matter satisfies nitrogen needs for the first few years after treatment. Nevertheless, once the residual nitrogen is exhausted, biological nitrogen fixation must become part of the revegetation formula if a maintenance-free system is to be restored.

The mature native forest of the Sudbury area contains no leguminous species, nor do

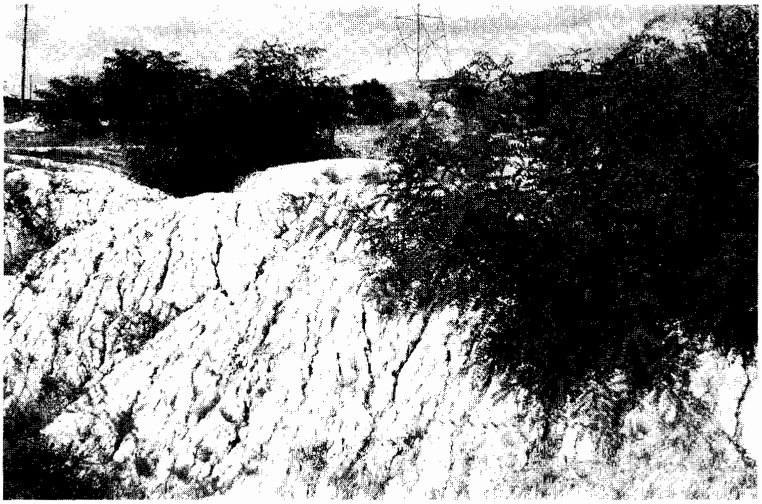

FIGURE 13.8. Black locust growing on gullied clay soils east of the abandoned Coniston smelter.

leguminous species play a role in succession after disturbance. The only common nitrogen-fixer in upland sites is sweet fern, which plays a role in jack pine succession. In the Sudbury area, relict stands of sweet fern occur on the barrens and often colonize sites that have been limed but not necessarily seeded. Because volunteer establishment of sweet fern on restored sites is intermittent, acid-tolerant, cold-hardy, and easily obtainable, nitrogen-fixing species such as birdsfoot trefoil and Alsike clover are incorporated into the seed mixture.

On difficult sites, such as the silty clay "badlands" where the direct seeding approach does not work, the small leguminous tree black locust (*Robinia pseudo-acacia*) is planted (Beckett and Negusanti 1990) (Fig. 13.8). In its native habitat, black locust is a vigorous pioneer colonist of disturbed sites in the southeastern deciduous forest. Its tendency toward a growth decrease and possible mortality after 10–20 years (Boring and Swank 1984) suggests that it might play a useful role in soil stabilization and soil humus and nitrogen buildup before giving way to native woody species rather than persisting as an aggressive weed. Also, it will be interesting to observe what effect black locust will have on community dynamics, because there are reports that this species provides a favorable environment for colonizing by other woody species (e.g., Ashby et al. 1980).

Cycling and Fate of Potentially Toxic Metals

A potential negative effect of revegetation might be the translocation of metals by plants from the soil into the terrestrial food chain. Certainly, the copper and nickel contents of the herbaceous vegetation first established on reclaimed land are approximately 10 times as high as Freedman and Hutchinson's (1981) "normal" values (Winterhalder et al. 1984). In the case of tree species, Beckett and Negusanti (1990) compared 3-year-old jack pine needles from a revegetated site with those from a control site 50 km from Sudbury and found elevated levels of aluminum, copper, and nickel in the former. Nevertheless, liming itself reduces the potential metal uptake by plants. Winterhalder et al. (1984) have shown that with metal-tolerant strains of tufted hairgrass, liming brings about a significant decrease in leaf content of aluminum, copper, and nickel (aluminum > nickel > copper).

Although the detoxifying effect of liming on soil is a complex one, the reduced availability of metals after liming can still be demonstrated in chemical terms alone. Total metals in the soil have shown a reduction on revegetated land over the 12-year period after liming as a result of uptake of metal into plants and loss to the general environment. Some changes have also taken place in untreated soils, and a reduction in water-soluble copper and nickel has been found in barren soils collected west of the inactive Coniston smelter, presumably due to a combination of pH amelioration, leaching, and erosion.

General Discussion

Cairns (1979) proposed three management options for the reclamation of mined land: (1) doing nothing, (2) restoring to the original condition, or (3) reclaiming to an ecologically improved and socially acceptable state. The burgeoning "restorationist" movement has the second option as its commendable goal, but as Cairns pointed out, this is rarely attainable, and the mutual acceptance of option 3 by ecologists and industry is the one most likely to lead to a nonadversarial and productive working relationship. The Sudbury approach appears to be a compromise of the sort proposed by Cairns, in that the goal is a quasi-natural functioning ecosystem. Nevertheless, wherever possible, barriers to the ultimate development of the ecosystem toward the "climax" should be removed (e.g., by providing nuclei of understory species and microbiota). In a later paper, Cairns (1983) split his second option into "rehabilitation," in which the reclamation moves in the general direction of restoration, and "alternative ecosystems." Clearly, the Sudbury experience falls into the rehabilitation category.

In the Sudbury Land Reclamation Program (Winterhalder 1985, 1987, 1988), the use of minimal amelioration and minimal seeding rates makes for a lean, diverse physical environment, with sparse initial cover, which is very suitable for colonization by a diversity of species and probably by a diversity of genetic variants of some of the species. It also appears to achieve the twin goals of optimal cover and optimal diversity, considered by Davis et al. (1985) to be incompatible.

Based on a relatively short time frame of 15 years, the Sudbury story appears to be an exception to Bradshaw's (1987b) statement that "in the case of metal-contaminated sites . . . , the nature of the toxicity is such that direct treatment is not completely satisfactory." Bradshaw goes on to suggest that one should look to metal-tolerant ecotypes as the answer, but the Sudbury experiment strongly suggests that in the case of metal-contaminated soils (if not in the case of mine wastes), once the initial barrier to plant growth is overcome, the vegetation itself will continue to ameliorate the soil by the production of insulating leaf litter and metal-chelating humus, by transporting bases to the surface, by fixing nitrogen, and by modifying the microclimate.

Ecologists can learn a great deal from the observation of ecosystem degradation and restoration (Cairns 1981; Bradshaw 1987a). The dynamics of the Sudbury landscape will provide research opportunities for decades to come, especially the chance to compare parallel changes in treated and untreated land.

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