THE USE OF MANUAL SURFACE SEEDING, LIMING AND FERTILIZATION IN THE RECLAMATION OF ACID, METAL-CONTAMINATED LAND IN THE SUDBURY, ONTARIO MINING AND SMELTING REGION OF CANADA[1]

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Abstract.--Ground dolomitic limestone applied manually to the surface of acid, metalliferous soils triggers plant establishment from the seed bank or from broadcast seeds. Native woody plants are rapidly colonizing the approximately 2500 ha of barren land that have been revegetated manually in this way, funded by government employment-creation programmes.

INTRODUCTION

Sudbury, Ontario (46°30'N 81°00'W) is situated on the southern edge of the Precambrian Shield, in a glaciated landscape characterized by a mosaic of rock outcrops, glacial till deposits and lakes. It lies near the northern limit of Braun's (1950) Hemlock-White Pine-Northern Hardwoods vegetational Region. Its original vegetation included extensive stands of Pinus strobus (White Pine), P. resinosa (Red Pine) and P. banksiana (Jack Pine) on rocky and other well-drained sites, Thuja occidentalis (White Cedar) swamps and Picea mariana (Black Spruce) bogs on lowland sites, and more limited stands of Northern Hardwoods (e.g. Acer saccharum (Sugar Maple), and Betula alleghaniensis (Yellow Birch)), in sheltered situations with rich soils. Extensive logging of the larger Red and White Pines initiated in 1872 was followed by mining and smelting of sulphide ores from 1886 onwards. With mining came the use of smaller trees as mine timbers and as fuel for the open roast beds, while prospectors often burned the remaining vegetation and duff to reveal the bedrock below. Sulphur dioxide from the ground-level roast beds killed remaining vegetation in their vicinity between 1888 and 1929, while smoke from the smelters, containing not only sulphur dioxide, but also copper, nickel and iron particulates, leached and acidified the soil, contaminating it with toxic copper and nickel as well as releasing toxic aluminum from the soil minerals (Winterhalder, 1984).

The existing soil, having lost its protective vegetation cover, suffered extensive erosion, exacerbated by the intense frost-heaving and needle ice formation that resulted once the insulating leaf-litter was gone (Sahi, 1983). Fires, whether caused by lightning or by man, continued as a significant factor in the degradation of this open environment, with its abundance of tinder-dry dead plant material. Together, these factors formed an interacting holocoenotic environmental complex, illustrated by figure 1.

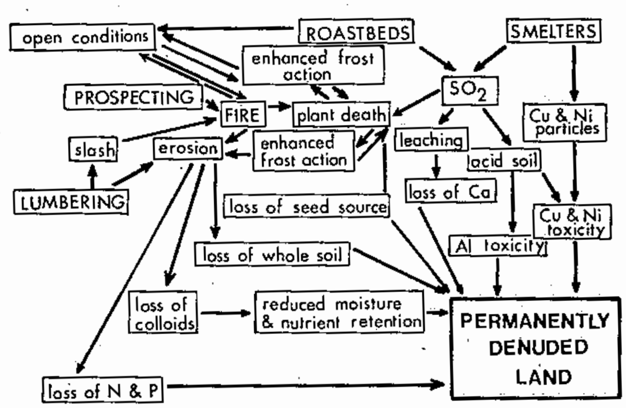

Figure 1.--A simplified representation of some of the major factor interactions leading to the formation of barren land.

The net result was the creation of 10,000 ha of completely barren land (figure 2), as well as 36,000 ha of open woodland, either dominated by stunted and coppiced Betula papyrifera (White Birch) and Acer rubrum (Red Maple) referred to by Amiro & Courtin (1981) as the "Birch Transition community" (figure 3), or by Quercus borealis (Red Oak).

[1]Paper presented at the 1985 National Meeting of the American Society for Surface Mining and Reclamation (Denver, Colorado, October 8-10, 1985).

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Proceedings America Society of Mining and Reclamation, 1985 pp 196-204
DOI: 10.21000/JASMR85010196
https://doi.org/10.21000/JASMR85010195

In 1972, the smelter at Coniston and the iron ore sintering plant at Falconbridge were closed down, while Inco's three smokestacks at the Copper Cliff smelter were replaced by a 381 m stack and Inco's Iron Ore Plant cut back its sulphur dioxide emissions to 250 tonnes/day. With the resultant improvement in atmospheric quality, it was expected that existing stunted vegetation would begin normal growth and that barren areas would be quickly colonized. This only occurred to a limited degree. Existing White Birch and poplar trees grew more rapidly, while at the same time Agrostis scabra (Winterhalder, 1976; Balsillie, McIlveen & Winterhalder, 1978), multiple metal-tolerant Deschampsia caespitosa (Cox & Hutchinson, 1980) and in some areas, tolerant, indigenous Agrostis gigantea (Hogan & Rauser, 1979) increased their coverage of the moister barrens. On the stony hillsides in the vicinity of Coniston, scattered White Birch seedlings became established, while on barren hillsides near shrubby bogs, Betula pumila var. glandulifera began to move up the slopes.

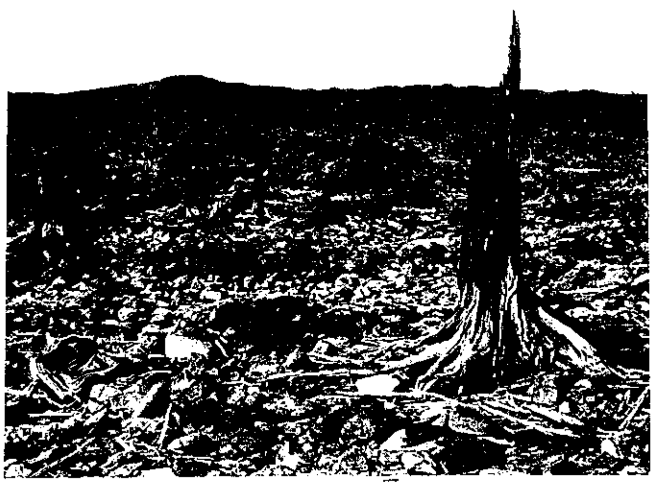
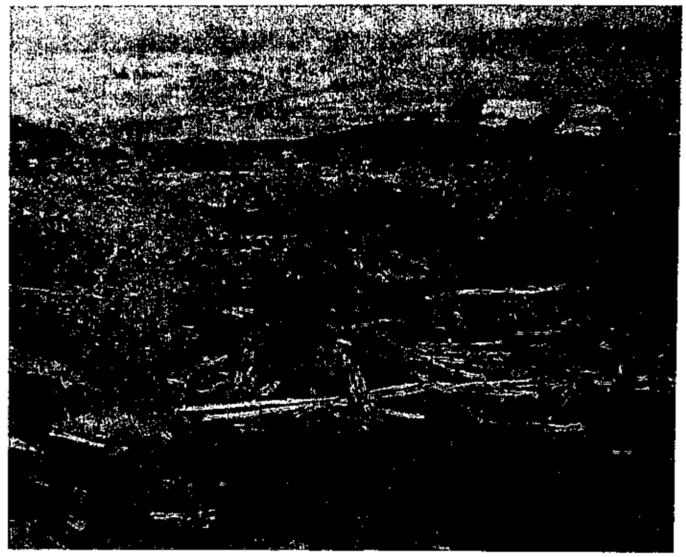


Figure 2.--White Pine stumps on a barren, stony hillside, 2 km northeast of the Copper Cliff smelter.

Figure 3.--Stunted White Birch with Red Maple in a late stage of regressive dieback, 6 km southwest of the Falconbridge smelter.

In many barren sites, however, no colonization occurred, as shown in figures 4 and 5, taken 15 years apart.



Fignre 4.--Barren site (foreground) 2 km north of the Coniston smelter, July 1967.

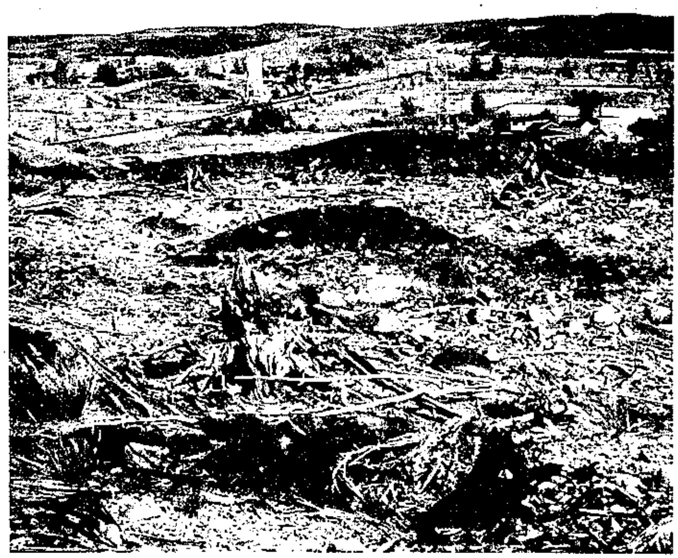


Figure 5.--Same site in July, 1982. The only plants present are two Agrostis scabra tussocks. despite the closure of the smelter in 1972.

Analysis of soil from the pollution zones surrounding the three smelters shows a pattern of decreasing pH and increasing copper and nickel contents as the smelters are approached. On barren sites, soil pH ranges from 2.0 - 4.5, while total copper and nickel content can each reach 1000 μg/g (Hutchinson & Whitby, 1974). "Available" copper, nickel and aluminum frequently approach 100 μg/g. Bioassay experiments showed that barren soils were inhibitory to root growth (figure 6), and that these soils could be detoxified by treatment with ground limestone.

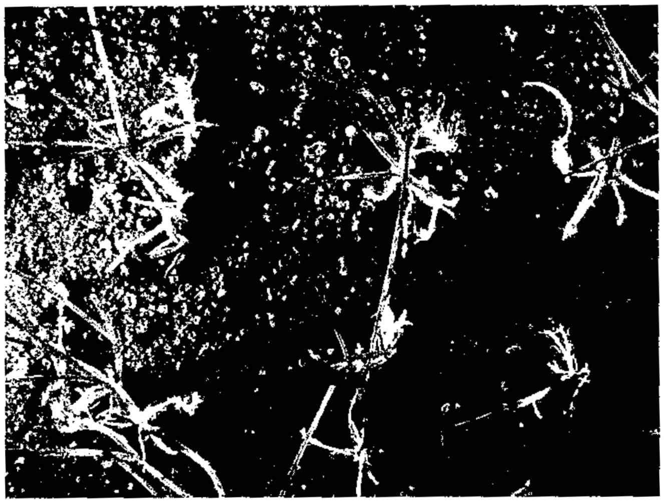


Figure 6.--Grass seedlings germinated on toxic soil develop numerous short "prop-roots" that do not enter the soil.

Sandy barren soils treated with limestone and seeded with Poa compressa (Canada Bluegrass), a drought-resistant species well suited to sandy soils, retained a grass cover for a number of years, but the plants did not spread beyond the limed area (figure 7).

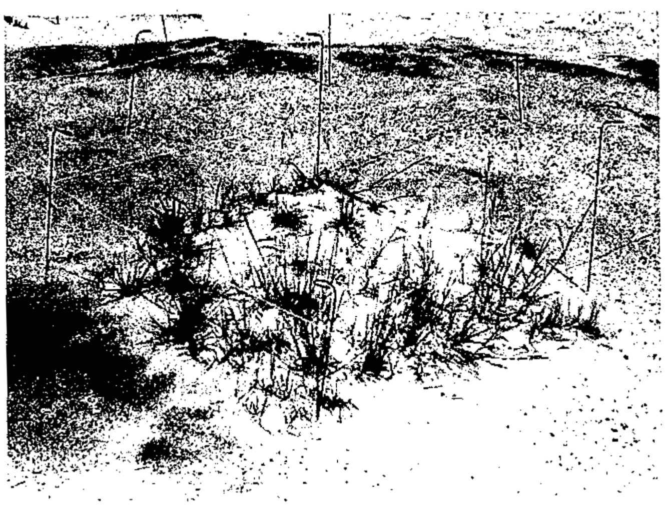


Figure 7.--A one-metre-square plot 4 km north of the Coniston smelter, six years after treating with limestone and seeding with Poa compressa.

Following limestone application, soil phosphorus emerged as the secondary limiting factor (figure 8).

A six-acre sandy, barren site in the valley of Coniston Creek was successfully treated in this way in 1974 using conventional agricultural machinery, and a number of herbaceous and woody species have colonized, including willows, poplars and the nitrogen-fixing shrub Comptonia peregrina (Sweet Fern)

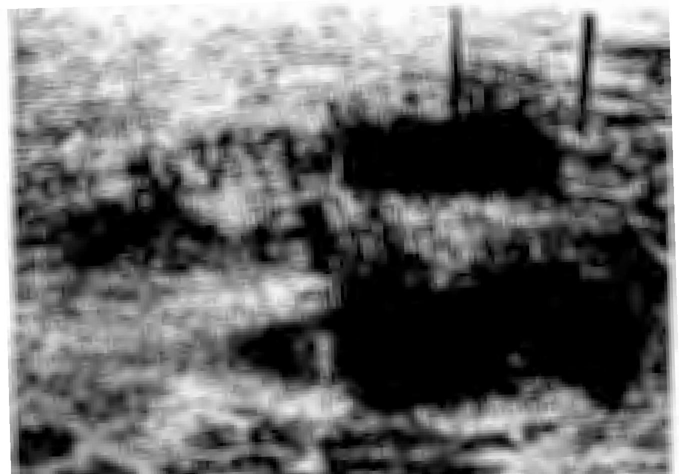


Figure 8.--The sparsely-vegetated one-metre-square plot on the left has been treated with limestone, the better-covered plots on the right with limestone plus superphosphate (4 km north of the Coniston smelter).

EARLY FIELD TRIALS

Since the percentage of land accessible to farm machinery is limited, attention was next turned to the barren hillsides. These consisted of rock outcrops with shallow soil pockets, as well as extensive slopes of partly-eroded soil covered by the layer of boulders and pebbles that was left behind as the finer materials were eroded away (figure 2). Earlier attempts to revegetate steep, stony slopes (e.g. Peters, 1978) had required the prior use of heavy landscaping machinery, and were too expensive to use on a large scale. In late summer of 1974, several one-metre-wide strips of rocky slope were treated manually with a surface application of ground dolomitic limestone (12 t/ha), 7-7-7 fertilizer with 40% urea-formaldehyde nitrogen (0.9 t/ha) and seed mixture (85 kg/ha). The constitution of the seed mixture is given in table 1.

Table 1.--Seed mixture used on test strips

Species		% Composition by volume
Agrostis gigantea	Redtop	33
Festuca rubra	Creeping Red Fescue	33
Poa compressa	Canada Bluegrass	15
Deschampsia flexuosa	Wavy Hairgrass [1]	9
Agrostis scabra	Tickle Grass [1]	5
Phalaris arundinacea	Reed Canary Grass	5

[1] Native species, seeds collected locally by hand.

Within a few weeks, germination occurred between and beneath the stony covering (figure 9). It appears that the stones acted as a mulch, trapping limestone, seeds and fertilizer, preventing erosion and conserving moisture.

Figure 9.--Seedlings developing between the stones that form a mantle over the soil.

A good grass cover was produced (figure 10), which was sustained over a number of years without further soil amelioration.

Figure 10.--One-metre-wide grass strips created by surface application of limestone, fertilizer and seeds, near Wahnapitae, 3.5 km east-northeast of the Coniston smelter.

Following the success of the one-metre-wide strips, two local elementary schools were invited to supply volunteers during mid-August of 1975 and 1977, to treat small patches of barren ground (0.5 ha) near their schools. In both cases, excellent plant cover was achieved.

THE OPERATIONAL PROGRAMME

In 1978, application for job-creation funds was was made to the Canadian Government by the Regional Municipality of Sudbury. These funds were for the purpose of hiring post-secondary students, who would apply the previously tested manual technique at the operational level. During the first year of the Sudbury Regional Land Reclamation Programme, 174 students were employed, 82 of them on liming, fertilizing and seeding. Pulverized dolomitic limestone was dumped at strategic sites, bagged by the students and distributed on the hillside at a spacing that gave an approximate coverage of 10 t/ha when spread. Fertilizer (5:20:20) was spread at a rate of 0.4 t/ha, using a hand-operated "Cyclone" seeder, followed by seed application at a rate of 45 kg/ha using the same spreader. In 1978, 115 ha of barren land were grassed in this way. During the years that followed, 200 - 300 students and other unemployed persons were hired each year, with 1983 being exceptional in that 1300 persons were employed, many being unemployed mine workers hired on joint Federal-Provincial funding. Between 1978 and 1984, a total of 2500 ha of land have been treated in this way, approximately 25% of the total barren area (Lautenbach, 1985).

The seed mixture used in the Regional Land Reclamation Programme (table 2) is a modification of that used in the earlier trials. Reed Canary Grass, a relatively unsuccessful species, was dropped, while the percentage of Creeping Red Fescue, which was only successful in certain microhabitats, was reduced. Since native grass species were found to colonize readily by natural dispersal, they were also omitted from the mixture. In fact, although Deschampsia flexuosa would appear to be an appropriate species for rocky hillsides, it is in fact D. caespitosa that colonises such sites, especially where there is ample moisture such as in seepage areas or at the base of rock-outcrop catchments. Agrostis scabra, although a highly tolerant species on contaminated soils, is a somewhat ephemeral perennial, and contributes little towards creating a permanent plant community (Winterhalder, 1976). Two herbaceous, acid-tolerant legumes were added to the mixture, since nitrogen, although not limiting during the first year, becomes so shortly thereafter.

Table 2.--Regional Land Reclamation Programme seed mixture[1]

Species		% Composition by weight
Agrostis gigantea	Redtop	20
Phleum pratense	Timothy	20
Poa compressa	Canada Bluegrass	15
Poa pratensis	Kentucky Bluegrass	15
Festuca rubra	Creeping Red Fescue	10
Lotus corniculatus	Birdsfoot Trefoil	10
Trifolium hybridum	Alsike Clover	10

[1]The mixture varied slightly from year to year.

In the small-scale trials, good quality control had been possible in the application of ameliorants and seeds, but the spreading of limestone, fertilizer and seed in the larger operational programme was distinctly patchy, creating a mosaic of differing soil pH, nutrient status and seed supply. This proved beneficial with respect to species diversity, since colonization by volunteer species was much more extensive than in the evenly-treated smaller plots. Figures 11 and 12 show a typical site before and after vegetation establishment.

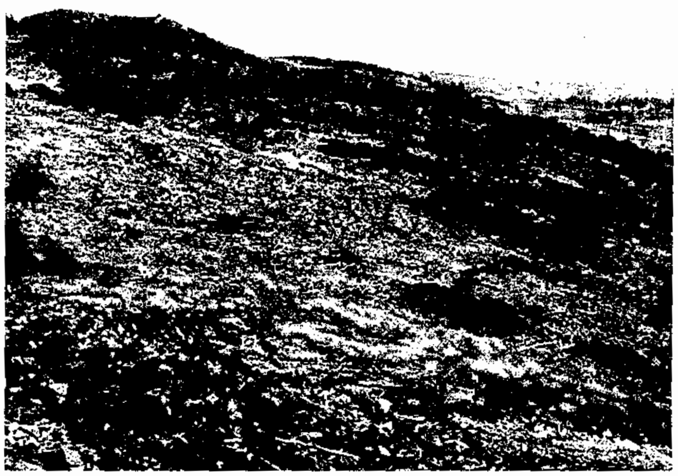


Figure 11.--Almost barren hillside 3.5 km northwest of Coniston smelter, with scattered White Birch and Tickle Grass patches, shortly prior to treatment (August, 1979).

Figure 12.--Same hillside in June, 1985, covered by sown grasses and legumes and spontaneously colonizing birches.

LIMING AS A TRIGGER FACTOR

Occasionally, through accident or lack of materials, an area was limed but fertilizer and seeds were omitted. In such cases it was noted that, within a year, colonization by mostly woody plants occurred. This led to the setting up of a number of one-metre-square experimental plots on barren ground, to which a thin sprinkling of limestone was applied. It was found that colonization by Tickle Grass and White Birch occurred rapidly in these plots, as illustrated in figures 13 and 14.

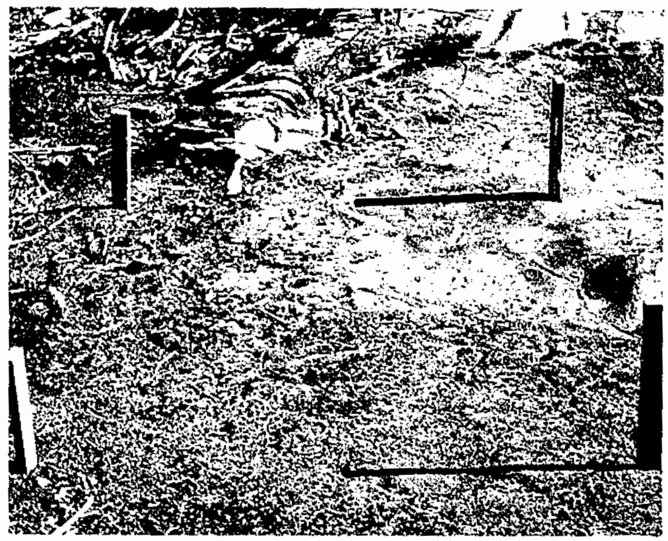


Figure 13.--One metre-square plot on bare area with partial Pohlia nutans cover near Garson, 5 km north of Coniston smelter and 6 km southwest of Falconbridge smelter, just prior to limestone application (September, 1979).

Figure 14.--Same plot in June, 1985, showing establishment of Betula papyrifera.

Some birch mortality occurred as a result of winter frost-heaving, an important environmental factor in these exposed, plant-litter-free soils (Sahi, 1983). However, most of the root systems produced by these birch seedlings in the limed soil were sufficient to prevent their complete uprooting by frost action and subsequent death. At the Garson site, based on five one-square-metre plots, 41% of the seedlings showed signs of frost-heaving during their first winter, but mortality was only 33%. Over a period of four years, the actual number of Birch seedlings decreased at this site, while the number of Tickle Grass tussocks increased (figure 15).

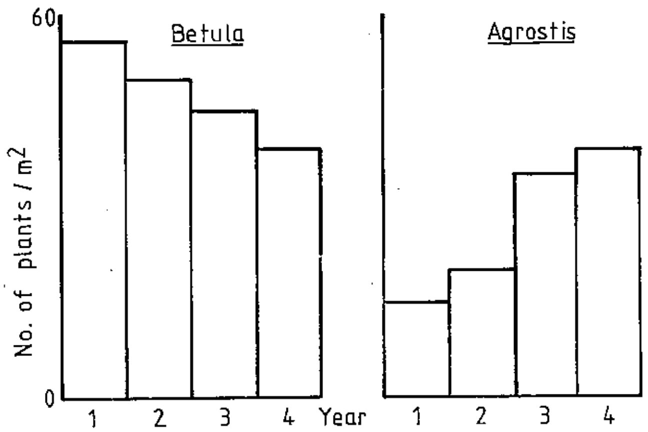


Figure 15.--Mean number of White Birch and Tickle Grass individuals found in five one-metre-square limed plots near Garson over four years following liming.

The reduction in seedling numbers was accompanied by an increase in percent cover. Table 3 shows final Importance Values (based on percent cover and percent frequency) for species colonizing 12 one-metre-square limed plots on varied terrain, measured five to six years after treatment.

Table 3.--Importance Values (Cover/Frequency Index[1]) for species colonizing 12 limed one-metre-square plots.

Species	Mean % Cover	% Frequency	Importance Value
Woody			
Betula papyrifera	41.3	66.6	47.5
Salix spp.	3.6	50.0	11.5
Populus tremuloides	3.3	41.7	9.8
Populus grandidentata	0.8	8.3	2.1
Herbaceous			
Agrostis scabra	5.6	83.3	18.8
Rumex acetosella	1.3	8.3	2.5
Aralia hispida	0.8	8.3	2.1
Conyza canadensis	0.1	8.3	1.5
Festuca rubra[2]	0.1	8.3	1.5
Phleum pratense[2]	0.1	8.3	1.5
Poa compressa[2]	0.1	8.3	1.5

[1]Relative Frequency + Relative Cover / 2
[2]Seeds blown in from nearby revegetated area

These data suggest a tendency for birches to become dominant over a period of several years, even when poplars and willows initially colonize in greater numbers.

COLONIZATION OF REVEGETATED AREAS

Revegetated areas are being monitored annually, and already some interesting changes appear to be taking place. Early herbaceous colonizers include Yarrow (Achillea lanulosa), Pearly Everlasting (Anaphalis margaritacea) and a sedge (Carex aenea) (Winterhalder, 1983). The gradual increase in Importance Value (Relative Cover + Relative Frequency / 2) of Pearly Everlasting is shown in figure 16.

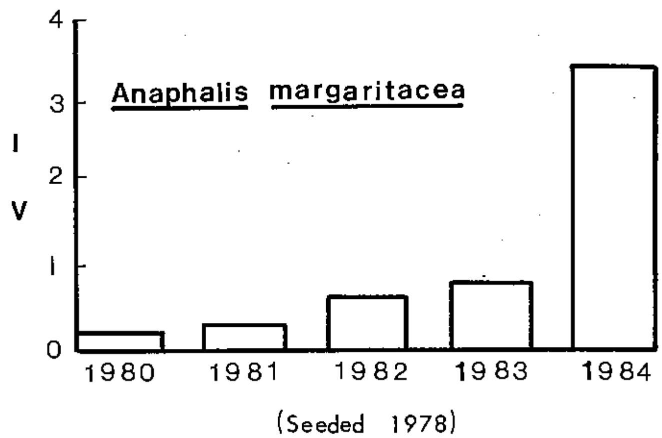


Figure 16.--Importance Values for Anaphalis margaritacea, 1-3 km east of the Coniston smelter, over a five-year period following treatment.

While grass cover appears to be falling off, that of nitrogen fixers, especially Birdsfoot Trefoil is increasing rapidly (figure 17).

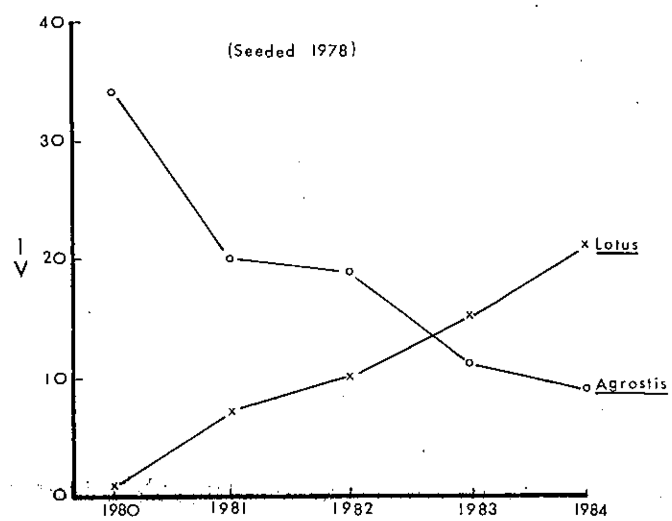


Figure 17.--Importance Values for Agrostis gigantea and Lotus corniculatus, 1-3 km east of the Coniston smelter, over a five-year period following treatment.

Also on the increase is cover by woody colonists such as Trembling Aspen and willows. This is particularly well shown along Highway 144, northwest of Sudbury (figure 18).

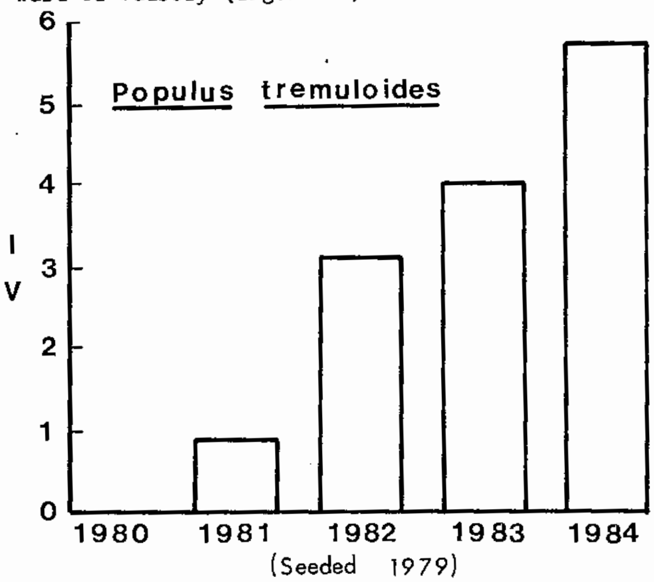


Figure 18.--Importance Values for Populus tremuloides, 2 km northeast of Copper Cliff smelter, over a four-year period following treatment.

So far, the woody colonists have been species that possess wind-dispersed seeds. The hairy seeds of the poplars and willows can be carried a considerable distance. The winged samaras of the White Birch may not be carried very far, but there is often an occasional seed tree in the vicinity of a barren site. So far there has been no evidence of spontaneous establishment of conifers. The reason for this is still a matter for conjecture, but the relative rarity of coniferous seed trees and the lack of a non-toxic mineral seed bed must be contributing factors.

TREE AND SHRUB PLANTING PROGRAMME

Because there has so far been no spontaneous colonization by conifers, a programme of conifer planting was initiated in 1979. Both bare-root and container (Japanese Paper Pot) stock of Red, Jack and White Pine, as well as White Cedar and European Larch (Larix decidua) have been planted, with Jack Pine giving the best results (figure 19).

Experimental shrub plantings have also been made, using Soapberry (Shepherdia canadensis) and Bearberry (Arctostaphylos uva-ursi), transplanted from Manitoulin Island. The former is a well-known symbiotic nitrogen-fixer. The latter, a woody creeper, is not known to fix nitrogen, but the formation of nitrogen-fixing nodules has been reported from Alaska in another member of the genus (Bond, 1967). The green, healthy appearance of Bearberry plants on the nitrogen-deficient reclaimed Sudbury sites suggests that the role of the species in the nitrogen cycle is worth further investigation.

Figure 19.--Jack Pines planted on previously grassed site near Wahnapitae (3.5 km east of the Coniston smelter), planted spring 1979, photographed July 1983.

DISCUSSION

Limestone as a Trigger Factor

The most striking aspect of this study is the fact that surface application of pulverized dolomitic limestone detoxifies the soil, thereby acting as a "trigger factor" (Winterhalder, 1983a) and allowing the immediate establishment of native plants from the existing seedbank and from seeds that blow in. Following limestone application, growth of roots is no longer inhibited, and they can enter the soil freely, giving them access to moisture and nutrients and giving the plant some anchorage against frost-heaving. Results of interaction experiments (Winterhalder, 1983a) indicate that the detoxifying effect involves both calcium nutrition and a neutralization component, which together modify the interacting toxic effects of aluminum, copper and nickel.

Seeding versus Non-seeding

Although experiments have shown that vegetation can be established by the application of dolomitic limestone alone, the practice of the Sudbury Regional Land Reclamation Programme is to apply, in addition, fertilizer and a grass-legume seed mixture. Since public funds are used on the project, and since a prime objective is image-enhancement, the Regional Government favours the rapid greening achieved by a complete grass cover in the first year following treatment. A second advantage of seeding with agronomic species is the resulting establishment of nitrogen-fixing herbaceous legumes, probably essential to the developing ecosystem. The fertilizer that is applied has a relatively low nitrogen content (6-24-24), and legumes, especially Birdsfoot Trefoil, spread rapidly under these nitrogen-deficient conditions.

There are, however, a number of arguments that can be made in support of using limestone alone, rather than limestone, fertilizer and seed. Not only is there an economic advantage to the simpler procedure, but the risk of eutrophication of watercourses and lakes by widespread fertilization is avoided. To the ecologist or the phytogeographer, the use of the existing local native and naturalized flora as a seed source avoids the introduction of alien species into a system that it is hoped will eventually become stable, self-sustaining and quasi-natural.

In the balance, however, and from the point of view of the final structure of the plant community developed, there may be some advantage in using a light agronomic seed application along with the limestone, since this leads to an open spacing between woody colonizers. While too heavy a seed and fertilizer application gives a closed sward that cannot be colonized, unseeded sites tend to develop a closed canopy of birches or poplars approximately five years after establishment. Table 4 is a comparison of the plant cover achieved in two years in two contiguous 100 square metre plots. The first plot was treated with limestone alone, the second with limestone, fertilizer and seeds. Plant cover was assessed in each plot by using 25 regularly-placed 1-metre-square quadrats.

Table 4.--Percent Cover and Importance Value (Cover/Frequency Index) achieved in two years by sown species and colonizers on a limed, fertilized and seeded plot and on an unseeded, unfertilized limed plot.

Species	Seeded Plot		Unseeded Plot	
	% cover	IV	% cover	IV
Sown species				
Agrostis gigantea	14.1	25.5	2.5	13.8
Festuca rubra	9.9	20.7	0.0	0.0
Lotus corniculatus	5.3	13.3	0.0	0.0
Trifolium hybridum	3.8	8.9	0.0	0.0
Poa compressa	0.1	1.3	0.7	6.5
Phleum pratense	0.1	0.5	0.1	0.9
Poa pratensis	0.1	0.5	0.1	0.5
Woody colonizers				
Populus tremuloides	0.6	1.5	9.1	29.1
Salix spp.	0.1	0.9	5.5	20.1
Betula papyrifera	0.0	0.0	0.4	4.5
Populus grandidentata	0.0	0.0	0	3.2
Herbaceous colonizers				
Agrostis scabra	0.7	6.9	3.4	16.5
Carex aenea	0.0	0.0	0.3	2.1
Juncus brevicaudatus	0.0	0.0	0.1	1.3
Deschampsia caespitosa	0.0	0.0	0.2	2.1
Equisetum arvense	0.0	0.0	0.1	0.5
Rumex acetosella	9.4	17.9	0.0	0.0
Trifolium pratense	0.3	1.1	0.0	0.0
Chrysanthemum leucanthemum	0.1	0.5	0.0	0.0
Epilobium angustifolium	0.1	0.5	0.0	0.0
Total	44.7	100.0	22.5	100.0

It should be noted that, two years after treatment, the percent cover by living plants is twice as high in the seeded area as in the unseeded area. Furthermore, most of the approximately 50% of the ground not covered by living plants in the seeded area was covered by dead plant material. Woody plant cover is much higher in the unseeded site, however, as is the number of woody individuals (not included in the table). In the seeded plot, it is likely that the germination and establishment of woody species is inhibited by dense growth of grasses in the first year and by this plus dead plant material in the second season. It should be emphasized, however, that an extremely low colonization rate by woody species is characteristic of small experimental seeded plots, where application of ameliorant and seed is carried out with care. As mentioned earlier, the environmental mosaic formed by the more "careless" treatment prevalent in a manual, operational programme favours the establishment of woody species.

Although the unseeded plot had a total plant cover of only 22.5% two years after treatment, it is predicted that the canopy will almost certainly be closed within a few more years, and that intense competition will result. It should be noted that, although percent cover by birch was low at the time of assessment (August, 1985), a number of small seedlings were present. Judging by the results of the 1-metre-square limed plots (table 3), these seedlings may well dominate the canopy by the end of six years.

Prognosis

Only monitoring over a number of decades will tell whether a self-sustaining, maintenance-free plant community and ecosystem is a feasible end-product on the Sudbury barrens. The replacement of grasses by woody species may lead to renewed soil-erosion, unless the woody plants are able to produce a sufficient canopy and leaf litter cover to forestall this. The applied limestone will no doubt lose its efficacy as plant uptake of calcium and leaching of bases proceed. This deterioration in soil base status and pH should take place slowly enough, however, to apply gentle selection pressure on the plant populations present, ensuring that the most tolerant individuals and populations will eventually dominate.

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