THE EXPERIMENTAL USE OF VARIOUS COVERS AND NATIVE TRANSPLANTS FOR THE REVEGETATION OF THE KAM-KOTIA TAILINGS SITE, TIMMINS, ONTARIO[1]

by

Keith Winterhalder[2]

Abstract. The Kam-Kotia mine/mill complex was closed in 1972, leaving 275 hectares of sulphide-rich, acid-generating tailings. Surface tailings have a pH of around 2.5, and contain elevated levels of arsenic, zinc and copper. Preliminary revegetation field trials have investigated the effectiveness of covers such as gravel, loam and peat, at different depths and in different combinations, and of locally available neutralizing agents such as ground dolomitic limestone, marl and sewage incinerator ash. The survival and growth of a seeded grass-legume mixture on replicated 2 m x 2 m plots has been monitored for a one-year period, as has the surface moisture regime and the capillary rise of acid ground-water. Plant biomass data show that a loam covering or a gravel covering topped with loam are the most effective, but at least one more season of observation will be required to determine the relative vulnerability of different cover combinations to upward movement of acids. A second approach to revegetation has been the transplanting of metal-tolerant ecotypes of native species from acid, metal-contaminated soils of the Sudbury mining area such as *Deschampsia caespitosa* (Tufted Hairgrass), *Agrostis gigantea* (Redtop), *Scirpus cyperinus* (Wool Sedge) and *Betula pumila* (Dwarf Birch). Tufted Hairgrass, Redtop and Dwarf Birch proved to be most successful on well-drained microsites, the Wool Sedge doing better on moist sites. A third approach involved the transplantation of whole sods of peat and associated plants from a nearby bog, with considerable success. While this approach may not be feasible on an operational scale under current circumstances, in view of the expense and the concomitant destruction of a natural bog community, the situation will change if current plans to develop the horticultural peat industry in Northern Ontario come to fruition.

Introduction

Sulphide-bearing tailings can be the source of two distinct types of environmental problem. Firstly, the oxidation of sulphides near the surface leads to highly acidic pore water, and to a substrate that is unsuitable for plant growth. This creates an aesthetic problem, and a surface that is susceptible to erosion by wind and water. Secondly, the oxidation of sulphides leads to acid mine drainage. The aesthetic and stability aspects of the tailings can be solved by revegetation, but the acid mine drainage requires a more complex solution. Revegetation leads to the interception of a portion of the precipitation by plants, to be evaporated or transpired back into the atmosphere, while the presence of vegetation will, to some degree, reduce oxygen penetration into the tailings surface, thereby reducing sulphide oxidation. Nevertheless, revegetation rarely reduces acid mine drainage by more than a small percentage, especially if ferric-iron-rich ground water with a pH below 4.0 flows through the system, allowing for the oxidation of sulphides by the bacterium *Thiobacillus ferrooxidans*.

The study described below addresses only revegetation aspects of the problem; the use of a constructed wetland for effluent polishing will be investigated at a later time.

The Kam-Kotia mine/mill complex, located at Kamiskotia, 24 km northwest of Timmins (48°36' N 81°37' W), began operation in 1943. The ore was rich in chalcopyrite,

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[2] Keith Winterhalder is Associate Professor of Biology, Laurentian University, Sudbury, Ontario, Canada P3E 2C6.

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sphalerite, pyrrhotite and pyrite, and was mined primarily for its copper and zinc content. Following closure in 1972, the property reverted to the Crown without rehabilitation. The area requiring revegetation is a sulphide-rich, acid-generating tailings deposit covering 275 hectares, including impounded areas where the tailings form a consistently deep layer and non-impounded areas where the thickness of tailings is highly variable. Acid mine drainage from the tailings has a pH of around 2.5, and is high in arsenic, zinc and copper.

Prior studies (e.g that by the D. Comrie Consulting Ltd., 1987) recommended sophisticated and costly solutions. In 1990, the present author was funded by the Kam-Kotia Steering Committee to carry out a number of small-scale trials employing varied "low-tech", low-cost revegetation techniques.

The approach to the problem was three-pronged, investigating:

a. the use of a covering-material,

b. the transplanting of potentially tolerant plant material, and

c. the transplantation of intact bog-sods

The use of covering materials

Several different functions can be served by covering materials, alternatively referred to as "covering systems" (Parry & Bell 1985). They can serve as growth media for vegetation. They can act, if coarse-grained, as "valves", or what Parry & Bell (1985) refer to as "break layers", allowing the free downward percolation of precipitation, but reducing the upward movement of acid pore-water by capillary action. They can also serve, if fine-grained, as oxygen barriers, especially if they remain in a wet condition for long periods of the year (Nicholson *et al.* 1989, Barbour 1990). The most important characteristic of potential cover materials intended as oxygen-barriers is the proportion of fines; clays are subject to surface cracking, and the ideal material is high in the medium to fine silt range (Nicholson *et al.* 1989). However, availability and cost-effectiveness are overriding factors, and the current study investigates the potential usefulness of locally-available materials, alone and in combination. A rather special case of a locally-available covering material is that of intact bog peat, which is not only intended as an oxygen barrier, but is potentially self-maintaining, provided that an adequate moisture level and vegetation survival can be maintained.

Soil as a covering material. Soil is often used as a covering material in revegetating pyritic wastes. In this context, the soil acts as a growth medium, controls infiltration and runoff, and serves as a barrier to oxygen. Although the recommended thickness of the layer is often great (e.g. the Illinois Pollution Control Regulations require that coal gob piles be covered with a minimum of 1.3 metres of nontoxic material), Hoving & Hood (1984) have shown that 30 cm of soil is sufficient to impede pyrite oxidation. They also concluded, however, that whereas the use of a soil cover as an oxygen barrier is effective on fresh pyritic material, oxidation is difficult to stop once it has started.

Gravel as a covering material. The rationale for the use of coarse gravel as a covering for tailings is based on its porosity. Gemmell (1977) stresses the need for physical isolation between plant growth medium and toxic material, to prevent the contamination of the rooting zone by upward diffusion of toxic ions, such as that reported by Breeze (1973) for chromate ions. The rate of upward movement of acid ground-water by capillary action in a gravel is low, and acid ground-waters are easily washed out by rain. Gravel can be placed on top of tailings, and in turn covered with a finer material, the objective being the reduction of upward capillary movement of acid tailings pore water by the gravel, combined with the maintenance of a moisture-retaining layer on top, which will act as a partial oxygen barrier and as a plant growth medium (Spires 1975). Nicholson *et al.* (1989) support the use of the textured layering of fine materials over coarse materials to improve moisture retention in the fine layer, thereby reducing oxygen diffusion coefficients. Furthermore, a well-drained material underlying a fine-grained upper layer can actually impede downward movement of water (Nicholson *et al.* 1991).

The transplanting of potentially tolerant plant material.

A number of native, acid-tolerant plant species growing in the Sudbury area have been shown to have evolved ecotypes that are tolerant of copper and nickel, e.g. *Agrostis gigantea* (Hogan *et al.* 1977), *A. scabra* (Archambault 1991), *Betula pumila* (Roshon 1988), *Deschampsia caespitosa* (Cox & Hutchinson 1979), *D. flexuosa* (Archambault 1989), *Poa compressa* (Rauser & Winterhalder 1985). Although the spectrum of potentially toxic metals in the pore water of the Kam-Kotia tailings is different from that in the acid, metal-contaminated soils of the Sudbury area, it has been shown by Cox & Hutchinson (1979) that, at least in the case of *Deschampsia caespitosa*, ecotypes can be tolerant towards metals other than those which are elevated in the soil in which they grow. It therefore seemed worth investigating the possibility that such plants might be at least partially pre-adapted to the acid tailings growth medium. Gadgil (1969) has cautioned against an assumption that the results of metal tolerance tests can be used with confidence to select plants for reclamation, but it seems reasonable to assume that any internal factor that ameliorates the stress to which a plant is exposed will improve its chance of survival and success.

Materials

Growth media and base materials

Pit-run gravel was used both as a growth medium and as a base material.

"**Loam**", an approximately 50:50 screened mixture of "red loam" and "black loam", was used as a growth medium, either alone or over a gravel base.

Horticultural-grade peat was either used on its own as a growth medium, or else was mixed into the upper few centimetres of the gravel, where its function was to improve moisture-retaining capacity and to provide both a nutrient source and a nutrient-adsorbing material.

Bog peat served both as an oxygen-barrier and as a base for living bog-sods collected at the same bog.

Neutralizing agents

Ground Dolomitic Limestone containing 2% calcium and 12% magnesium, and having a $CaCO_3$-equivalent of 101%, was ground such that 5.4% passed a 100 mesh screen and 100% passed a 10 mesh screen. Unless stated otherwise, the application rate was 4 t/ha (1.6 kg per 4 m^2 plot).

Sewage Incinerator Ash is a bottom ash from the Ashbridges Bay Sewage Treatment Plant in Toronto. The material had been transported by truck and stock-piled in Timmins for possible future precious metal recovery. The major constituent of the ash (38%) is a calcium magnesium phosphate ($Ca_7Mg_2P_6O_{24}$), with 30% SiO_2, 15% Fe_2O_3 and 9% Al_2O_3. Unless stated otherwise, the application rate was 2 t/ha (0.8 kg per 4 m^2 plot).

Marl was obtained from the Pup lakes (formerly Twin lakes) area in west-central Thorneloe township, District of Temiskaming. It contained approximately 87% $CaCO_3$ and 2.2% $MgCO_3$. Unless stated otherwise, the application rate was 4 t/ha (1.6 kg per 4 m^2 plot).

Fertilizers

A 6-24-24 agricultural-grade fertilizer was used at a rate of 400 kg/ha (160 g/4 m^2plot)

Plant material

Seeds. The grass-legume seed mix had the following constitution:

Agrostis gigantea	Redtop	10%
Festuca arundinacea	Tall Fescue	30%
Phleum pratense	Timothy	20%
Poa compressa	Canada Bluegrass	10%
Poa pratense	Kentucky Bluegrass	20%
Trifolium hybridum	Alsike Clover	10%

The seed mixture was sown at a rate of 30 kg/ha (12 g/ 4 m^2 plot), and lightly raked into the plot surface.

<u>Transplanting stock</u>

The following plant material was collected from acid, metal-contaminated soils in the Sudbury area, where there was some evidence of acid- and metal-tolerance:

Tufted Hairgrass (*Deschampsia caespitosa*)
Redtop (*Agrostis gigantea*)
Wool Sedge (*Scirpus cyperinus*)
Dwarf Birch (*Betula pumila*)

All samples were collected with a large portion of native soil attached to the roots.

Methods

Seeded Plots

These were set up on the well-drained North Impounded Tailings. Their dimensions were 2 m x 2 m, with a 0.5 m sloped buffer zone. They were set up in triplicate, using a randomized block design. Plots fell into three categories:

<u>Direct amelioration of tailings.</u> Current knowledge of the chemistry of the tailings strongly suggests that direct revegetation, however effective the neutralizer, will not succeed in the long run. One of the Kam-Kotia consultants' reports (Kilborn, 1983) recommended a limestone application rate of 334 tonnes/ha on the North Impounded tailings. This high application rate would, in the opinion of the present author, lead to a salinity problem. It was felt, therefore, that the potential of direct seeding should be checked experimentally, but using using a moderate liming rate in the first instance. Dolomitic limestone and marl were applied at 20 t/ha and ash at 10 t/ha, respectively, and raked into the surface of the tailings.

<u>Use of a gravel covering.</u> Gravel-based plots were constructed with gravel alone, or with gravel topped by commercially available peat moss which was worked into the top 5 cm of the gravel, or with gravel topped by the "loam" described above. Depth of both gravel and covering (where employed) were varied. In each case, one of the three neutralizers was raked into the surface, along with the standard fertilizer.

<u>Use of a loam covering.</u> In each case, one of the three neutralizers was raked into the surface, along with the standard fertilizer.

Transplant plots

<u>Direct transplants.</u> Potentially tolerant Sudbury plants were transplanted, in blocks of their own soil, into transects each having one of the following treatments: untreated tailings, limed tailings, or gravel over tailings.

<u>Plots involving the use of a living bog-sod cover.</u> In these plots, blocks of bog peat, complete with living vegetation, were placed on top of the tailings. Native peat from the bog was also used to form the 0.5 m shoulder. In this case, no neutralization, fertilization or seeding was carried out, since the intention was to have the bog plants survive in the peat block, which would impede oxygen penetration and tailings oxidation.

Monitoring

<u>A photographic record</u> of the plots was obtained several times during the summer of 1991.

<u>Soil samples</u> were obtained from the surface 10 cm of each plot on a weekly basis, and analyzed for pH and moisture content. Samples were retained for possible future metal analysis

<u>Biomass</u> was determined in August by harvesting the vegetation on 50% of each plot, drying it and weighing it.

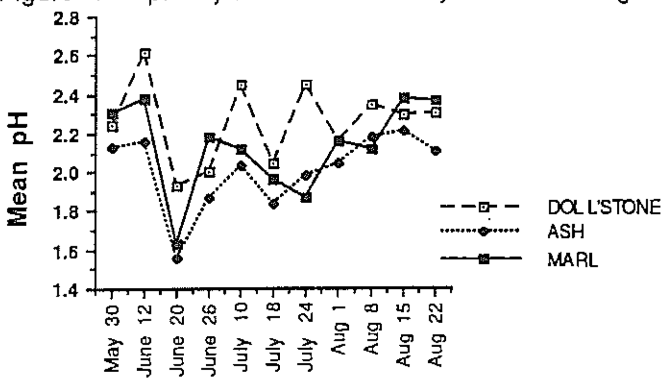
<u>Statistical treatment.</u> Data were subjected to Analysis of Variance and Duncan's Multiple Range Test using SPSS-X (ANOVA and ONEWAY).

Results and Discussion

Seeded Plots

Bare tailings. As predicted, there was no plant survival on directly-treated plots, although there was some germination and short-term growth. By the time monitoring began in May, following treatment the previous fall, the pH was already very low (Figure 1), and, despite fluctuations, it remained so .

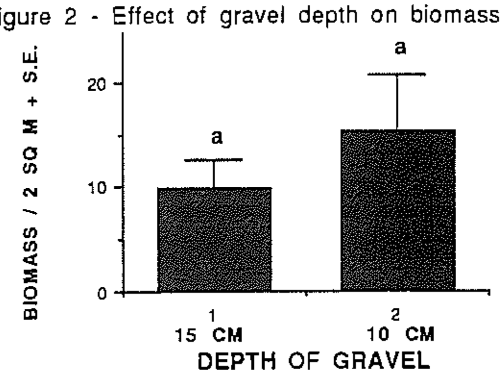
Figure 1 - pH dynamics of directly-treated tailings



In cases where sulphide concentrations in tailings are relatively low (e.g. 3%), the direct revegetation of tailings has been found possible, so long as an adequate amount of lime is applied (Young 1969, Michelutti 1974, Peters 1984). Costigan *et al.* (1981) concluded that, in highly pyritic spoils in general, even limestone application rates exceeding 100 t/ha may not prevent acidification. Preliminary trials on moderately acid molybdenum tailings in Colorado (Berg *et al.* 1975) suggested that liming at up to six times the base equivalent might be effective, especially if combined with leaching. However, the use of overburden as a cover has been found more feasible than direct treatment at the Climax molybdenum mine (Brown 1976), while at the Urad molybdenum mine, the tailings were covered with waste rock before revegetation was carried out (Brown & Jackson 1984). McIlveen (1982) found, in a growth chamber trial, that an agricultural limestone rate equivalent to 207 tonnes/ha was needed to allow the growth of grasses on tailings from the North Impounded site at Kam-Kotia. He acknowledged that, in view of the high lime requirement, it might be necessary to use a soil cover. Nevertheless, future direct-liming experiments at Kam-Kotia should include a series of limestone application rates, culminating at the 334 tonnes/ha recommended by the consultant, and monitoring should include conductivity measurements

Gravel-covered tailings. On gravel-covered tailings, biomass production was low, but survival was, in most cases, reasonable. As shown in Figure 2, biomass production was somewhat less on 15 cm of gravel than on 10 cm, but not significantly so.

Figure 2 - Effect of gravel depth on biomass production



Bars bearing the same superscript are not significantly different at the 5% probability level.

The reduced growth on the deeper gravel was presumably due to greater exposure, both in terms of drying and of wind-borne tailings abrasion. Figure 3 shows that moisture levels at a dry time and a moist time differ strikingly (significant at the <0.01 level). However, although moisture content appears to be marginally higher in the 10 cm gravel plots, the difference is not significant statistically.

Figures 4 & 5 show the changes in pH that occurred in the top 5 cm of the gravel plots. pH dropped sharply at first, but levelled off between pH 5 and pH 6. There seemed to be very little difference in pH dynamics between the 15 cm and 10 cm gravel plots .

Figure 3 - Surface moisture versus gravel depth

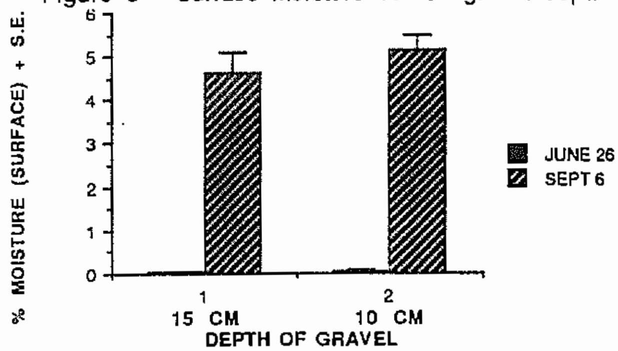


Figure 4 - Surface pH dynamics in 15 cm gravel plots

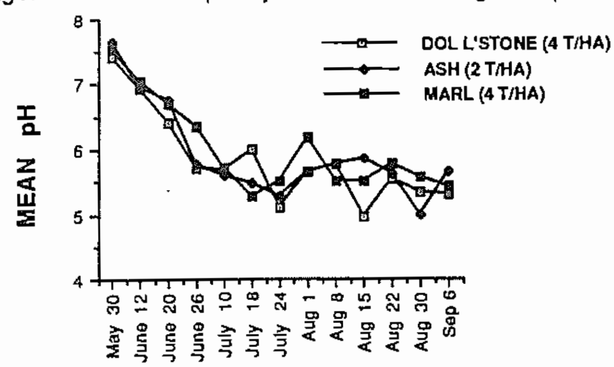
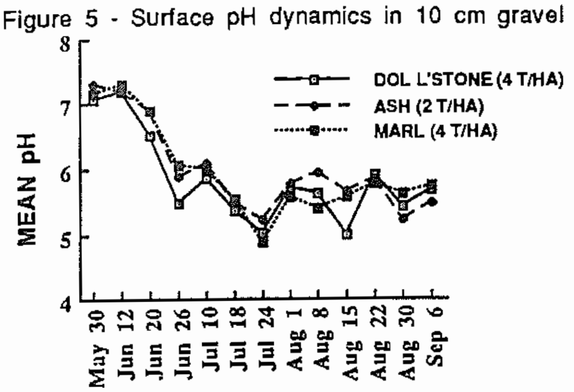


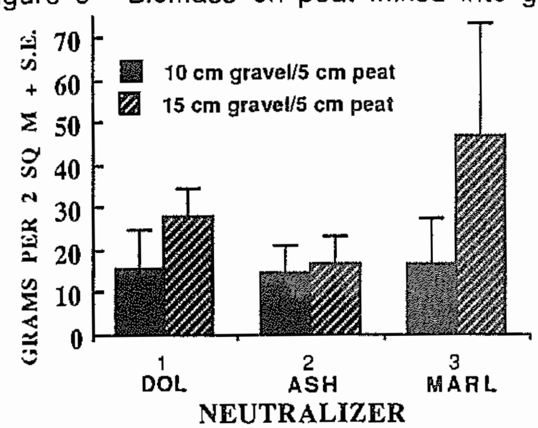
Figure 5 - Surface pH dynamics in 10 cm gravel plots



Past experience has shown gravel to be an effective covering, both with a loam covering (Spires 1975) and without (Michelutti 1974). However, a major disadvantage of gravel as a growth medium is its low nutrient content and its low nutrient-retaining capacity, as evidenced by the relatively poor biomass production seen in Figure 2. One way of improving nutrient content and retention is to mix an organic material, such as peat, into the surface. This would also improve the moisture-retaining capacity of the capping, without interfering with the "valve" effect of the gravel.

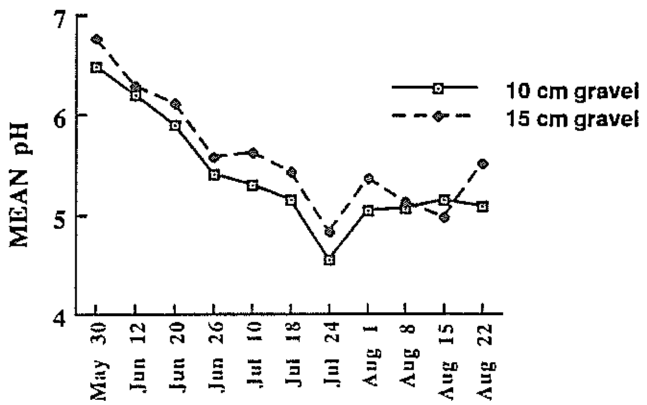
<u>**Gravel-covered tailings with peat worked into surface.**</u> As expected, biomass production was improved by mixing peat into the surface of the gravel (e.g. see Block C in Figure 13). However, contrary to the situation described for pure gravel, growth appeared to be better on 15 cm of gravel with 5 cm peat worked into the surface than on 10 cm with the same amount of peat (Figure 6). Despite the apparent consistency of this trend, the differences were not significant statistically.

Figure 6 - Biomass on peat mixed into gravel



If the apparent trend is real, it could be explained by the greater proximity of the peat's capillary-enhancing properties to the tailings surface, leading to greater upward movement of acid in the shallower gravel, a hypothesis that is supported by the apparent pH trend shown in Figure 7.

Figure 7 - pH dynamics on peat-gravel plots



Loam. On loam-covered tailings, standard errors about the means were usually too large to demonstrate a clear statistical difference, but when means are graphed, a definite trend can be seen. Overall, a gradual drop in pH occurred, but it only dropped permanently below 4 in the plot with a 5 cm cover. This is illustrated for all three neutralizers in Figures 8 - 10.

Figure 8 - pH dynamics on ash-treated loam

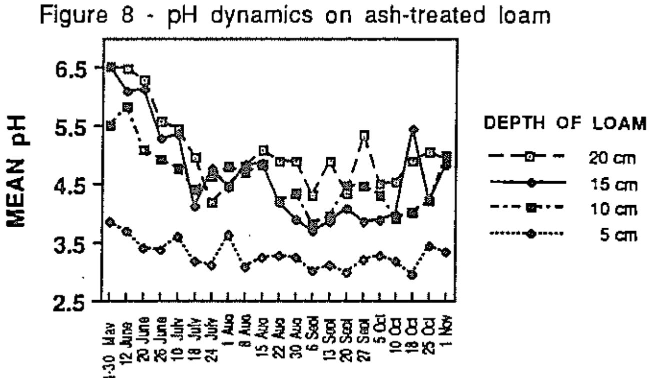


Figure 9 - pH dynamics on marl-treated loam

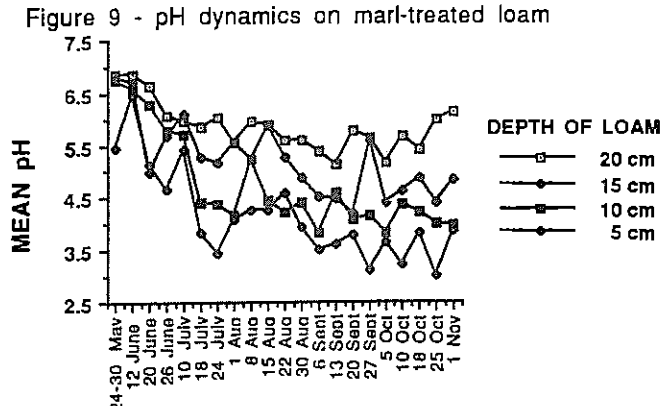


Figure 10 - pH dynamics on limestone-treated loam

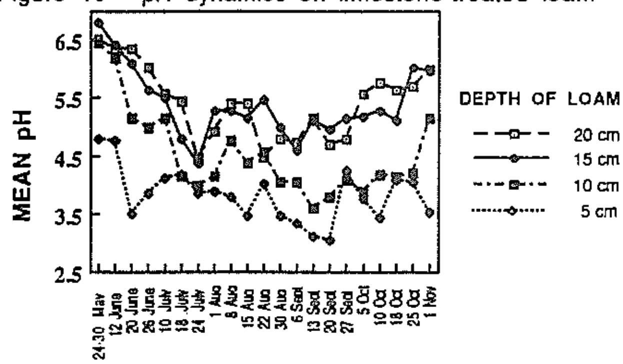
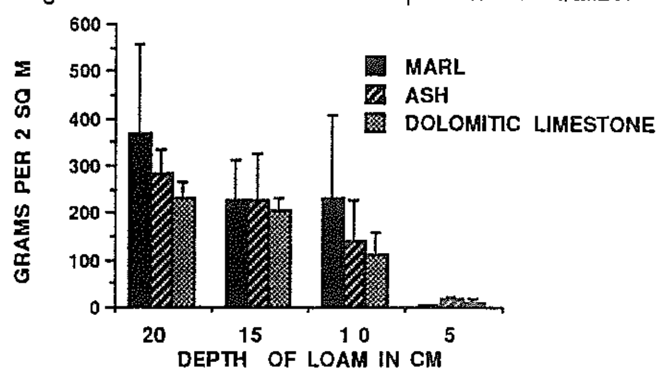


Figure 11 summarizes biomass production on loam. While the effect of neutralizer on biomass was not significant, an ANOVA showed that the effect of loam depth on biomass was significant at $P<0.01$.

Figure 11 - Biomass v loam depth and neutralizer



In terms of short-term biomass production (e.g. see Figure 13), loam is clearly superior to gravel as a cover. However, it is evident that the thickness of a loam cover should not be reduced below 10 cm. Indeed, in the long term, it may be found that even the 15 cm & 20 cm depths are insufficient. Drake (1986) found that shrubs survived consistently on 15 - 34 cm loess covers over acid coal spoils in Iowa, whereas tree species showed greater variability in response to covers of up to 75 cm. Gemmell & Goodman (1980) found that vegetation on 15 cm & 22.5 cm layers of pulverized fuel ash over zinc smelter wastes in the lower Swansea Valley showed acceptable growth up to four years, but by six years, large-scale dieback had occurred, probably due to the upward-diffusion of zinc ions. Borgegård & Rydin (1989) showed elevated metal levels in the surface of a soil layer up to a metre deep over copper tailings in Sweden, but did not show conclusively that this was due to upward diffusion. It appears that conclusions should not be drawn for a number of years after the establishment of the cover.

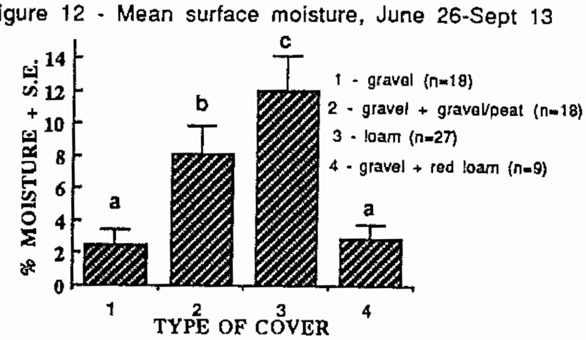
It should be noted that weeds formed a substantial proportion of the biomass on loam plots at Kam-Kotia. Drake (1986) considered competition by weeds on covers to have a negative effect on the growth of tree and shrub seedlings. It is expected, however, that weed growth will diminish after the first year, and that tree and shrub colonization or planting will be delayed for at least a year at the operational scale.

Effectiveness of neutralizers, at the levels used, appears to follow the sequence of marl>ash>dolomitic limestone.

General

Figure 12 shows the mean moisture levels of the different covers for most of the warm period. As expected, loam exhibits the best moisture-retention.

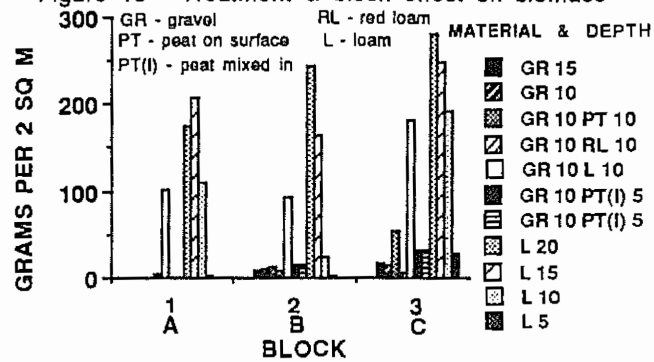
Figure 12 - Mean surface moisture, June 26-Sept 13



Bars with the same superscript do not differ significantly at the 5% probability level.

From Figure 13, it is clear that Block C, which is located within the shelter of dead treetops, has a more favourable microenvironment than the other blocks. McIlveen (1982) correctly suggested that the dead trees at Kam-Kotia, if allowed to remain, might afford protection from wind and blowing tailings. It is also clear from Figure 13 that a 15-20 cm layer of loam is likely to give the best biomass, with 10 cm of gravel covered by 10 cm of loam the second-best.

Figure 13 - Treatment & block effect on biomass



It is hoped that future observations on the upward-movement of acidified tailings water will determine whether the gravel-loam combination is indeed preferable to the loam alone.

Transplant Plots

Direct transplant plots. No quantitative data are available at this time, but it can be stated that there was a good survival rate overall. Dwarf Birch was most successful on the North Unimpounded site, where the tailings deposit is shallow, while Wool Sedge fared better on the South Unimpounded site, which is both shallow and moist. Tufted Hairgrass and Redtop did well in all sites. A quantitative assessment will take place in 1992.

Bog Sod Plots. All bog species remained vigorous during the first year of establishment.

General Discussion

It is clearly desirable to put waste products to use in revegetation (Parizek 1987). Gemmell (1981) concluded that the use of lime wastes in reclaiming acid colliery spoils involved no ecological disadvantages, but that several economic advantages were evident. The same might be said of the use of Incinerator Ash and Marl at Kam-Kotia, based on our current knowledge. It will, however, be necessary to carry out leaching column trials with incinerator ash before conclusions can be drawn, because of the possibility of contamination of ground water by such elements as arsenic (8.5 µg/g in ash), cadmium (35 µg/g), chromium (1700 µg/g), copper (2500 µg/g), lead (600 µg/g), nickel (240 µg/g) and zinc (4070 µg/g). Leaching tests carried out for the Municipality of Metropolitan Toronto showed that, although several elements in incinerator ash leachate exceeded the criteria in Schedule 4 of Regulation 309 of the Ontario Environmental Protection Act, they were not high enough to qualify the ash as a Hazardous or Registerable Waste. Most documented cases of ash being used in revegetation involve power station fly ash, e.g. Capp (1978) and Buck & Houston (1988). Although there have been other examples of sewage incinerator ash being transported for precious metal recovery (e.g. Toronto ash to Noranda Mines in Timmins, New York ash to Kirkland Lake, Ontario and Los Angeles ash to Murdochville, Québec), there is little evidence in the literature of the use of sewage sludge incinerator ash as a neutralizer for revegetation. The disadvantage of using sewage sludge ash rather than unburned sewage sludge is that the beneficial effects of organic material have been lost. On the other hand, advantages include the presence in the ash of free bases, which play a neutralizing role, and the fact that potentially harmful organics and microorganisms have been burned off.

Ames (1979), in a column study, found a gravel "break" layer effective in preventing migration of acid, iron, aluminum, zinc and copper from tailings into surface soil, and Spires (1975), in a field study, found a 7.5 cm layer of crushed slag between highly pyritic tailings and an organic soil similarly effective. However, the effectiveness of the use of gravel below a loam growth medium as a "valve" can only be judged over a period of several years, since there may be a tendency for fine material to wash into the coarse -grained layer, and root growth in the coarse layer may create new capillary channels. It is usually recommended (Parry & Bell 1985) that a filter layer of some sort (such as filter cloth) be interposed between coarse and fine layers. Cline *et al.* (1980) used a layer of loose rocks, in addition to a filter barrier, to prevent the penetration of plant roots into mine wastes. It is likely that, once woody species become established at Kam-Kotia, root penetration will become a problem. Borgegård & Rydin (1989) found that, on copper tailings in Sweden, *Betula pendula* and *B. pubescens* roots penetrated soil layer up to 1m in depth

While one year is too short an experimental period to be able to draw firm conclusions, it appears that it may be feasible to use a cover material to revegetate the well-drained portion of the Kam-Kotia tailings. Preliminary results suggest that a loam covering or a gravel covering topped with loam would be most effective, but at least one more season of observation will be required to determine the relative vulnerability of different cover combinations to upward movement of acids.

The bog-sod transplant approach also shows promise, but it is probably neither economically feasible nor conservationally desirable to use this technique on a large scale, unless plans to develop the horticultural peat industry in Northern Ontario come to fruition. Furthermore, this approach would be far more useful at a fresh tailings site than on one where oxidation of sulphides is already well advanced. Reardon & Moddle (1985) found in a column experiment that a 30 cm layer of peat was not sufficient to exclude oxygen, but the current author predicts that an undisturbed block of bog peat will have a lower gas diffusivity than Reardon & Moddle's peat, which had been freeze-dried, packed into a column and rewetted. Brown (1991) has suggested the establishment of a muskeg peat cover on tailings to mitigate acid leaching. She proposes the pumping of wet peat onto the tailings by means of a slurry pump, and suggests that, with maintenance of a high water table, natural colonization by bog plants should occur. She recommends that the peat be amended with cellulosic wastes, to enhance methane production and thereby further reduce hydraulic conductivity. In the present author's view, the incorporation of extra cellulosic material would make the peat a less desirable growth medium for bog plants.

The potential usefulness of metal-tolerant transplants from the Sudbury area cannot be dismissed, especially if they used to increase taxonomic and genetic diversity by establishing them in difficult sites.

A major consideration will be the relative cost of different approaches and materials, and this will have to be balanced against environmental considerations in each case. It is not impossible that a combination of all three approaches will be found appropriate. A diversity of treatments would lead to environmental heterogeneity, itself leading to biotic diversity. In revegetation practice, it is desirable to bring about and maintain diversity at the ecotypic level, as well as at the species level (Winterhalder, 1988). If a heterogeneous environment is combined with high genetic diversity in the potential colonizers, a process of "ecological adjustment" will occur, in which "natural selection will adjust the species composition to meet the prevailing soil conditions" (Gemmell, 1977).

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References

Ames, S. 1979. Migration of acid substances in Sullivan tailings - a column study. In: Reclamation of Lands Disturbed by Mining, Proceedings of the 3rd Annual British Columbia Mine Reclamation Symposium, Vernon, March 1979. pp. 309-324.

Archambault, D.J.P.. 1989. Metal tolerance studies on populations of *Deschampsia flexuosa* from Northern Ontario. B.Sc. thesis, Laurentian University, Sudbury, Ontario, 65 pp..

Archambault, D.J.P. 1991. Metal tolerance studies on populations of *Agrostis scabra* Willd. (Tickle Grass) from the Sudbury area. M.Sc. Thesis, Laurentian University, Sudbury, Ontario. 118 pp..

Barbour, S.L. 1990. Reduction of acid generation in mine tailings through the use of moisture retaining cover layers as oxygen barriers: discussion. Canadian Geotechnical Journal 27: 398-401 http://dx.doi.org/10.1139/t90-051

Berg, W.A., E.M. Barrau & L.A. Rhodes. 1975. Plant growth on acid molybdenum mill tailings as influenced by liming, leaching and fertility treatments. In: Chadwick, M.J. & G.T. Goodman. The Ecology of Resource Degradation and Renewal. Blackwell:Oxford. pp. 207-222.

Borgegård, S. & H. Rydin. 1989. Biomass, root penetration and heavy metal uptake in birch in a soil cover over copper tailings. Journal of Applied Ecology 26: 585-595 http://dx.doi.org/10.2307/2404084

Breeze, V. 1973. Land reclamation and river pollution problems in the Croal Valley caused by waste from chromate manufacture. Journal of Applied Ecology 10: 513-525.
http://dx.doi.org/10.2307/2402299

Brown, A. 1991. Proposal for the mitigation of acid leaching from tailings using a cover of muskeg peat. Proceedings of the Second International Conference on the Abatement of Acidic Drainage, Montréal, September 1991. Vol.2, pp.517-527.

Brown, L.F. 1976. Reclamation at Climax, Urad and Henderson Mines. Mining Congress Journal 62(4): 42-43, 49-51.

Brown, L.F. & C.L. Jackson. 1984. Reclamation of the Urad molybdenum mine, Empire, Colorado. Minerals & the Environment 6(2): 77-82.
http://dx.doi.org/10.1007/BF02072658

Buck, J.K. & R.J. Houston. 1988. Direct revegetation of anthracite refuse using coal fly ash as a major soil amendment. In: Mine Drainage and Surface Mine Reclamation: Vol. 2, U.S. Bureau of Mines Information Circular 9184. pp. 236-245.

https://doi.org/10.21000/JASMR88020236

Capp, J.P. 1978. Power plant fly ash utilization for land reclamation in the eastern United States. In: Schaller & Sutton, eds., Reclamation of Drastically Disturbed Lands, ASA-CSSA-SSSA : Madison. 339-353.

Cline, J.F., K.A. Gano & L.E. Rogers. 1980. Loose rock as biobarriers in shallow land burial. Health Physics 39: 497-504. http://dx.doi.org/10.1097/00004032-198009000-00008

Comrie, D. (Consulting Ltd.) 1987 Kam-Kotia Project Final Report. 147 pp.

Costigan, P.A., A.D Bradshaw & R.P. Gemmell. 1981. The reclamation of acidic colliery spoil. I. Acid production potential. Journal of Applied Ecology 18: 865-878 http://dx.doi.org/10.2307/2402377

Cox, R.M. and T.C. Hutchinson. 1979. Metal Co-tolerance in the Grass *Deschampsia cespitosa*. Nature 279 (5710): 231-233. http://dx.doi.org/10.1038/279231a0

Drake, L. 1986. Survival and growth of conservation shrubs and trees, with thin-cover reclamation on acid substrate, Iowa, U.S.A.. Environmental Geochemistry and Health 8(3): 62-67. http://dx.doi.org/10.1007/BF02311023

Gadgil, R.L. 1969. Tolerance of heavy metals and the reclamation of industrial wastes. Journal of Applied Ecology 6: 247-259. http://dx.doi.org/10.2307/2401539

Gemmell, R.P. 1977. Colonization of Industrial Wasteland. Edward Arnold: London. 75 pp..

Gemmell, R.P. 1981. The reclamation of acidic colliery spoil. II. The use of lime wastes. Journal of Applied Ecology 18: 879-887. http://dx.doi.org/10.2307/2402378

Gemmell, R.P. & G.T. Goodman. 1980. The maintenance of grassland on smelter wastes in the Lower Swansea Valley. III. Zinc smelter waste. Journal of Applied Ecology 7: 461-468. http://dx.doi.org/10.2307/2402341

Hogan, G.D., G.M. Courtin and W.E. Rauser. 1977. Copper Tolerance in Clones of *Agrostis gigantea* from a Mine Waste Site. Canadian Journal of Botany 55 (8): 1043-1050. http://dx.doi.org/10.1139/b77-122

Hoving, Sheryl J. & William C. Hood. 1984 The effects of different thicknesses of limestone and soil over pyritic material on leachate quality. 1984 Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation, Lexington, Kentucky, December 2-7, 1984. pp. 251-257.

Kilborn Limited. 1983. Kam-Kotia Tailings Reclamation Project. Final Report to the Ontario Ministry of the Environment. Executive Summary.

McIlveen, W.D. 1982. Preliminary evaluation of tailings material at Kamiskotia for purposes of reclamation. Unpublished Report, Ontario Ministry of the Environment, Sudbury. 19 pp.

Michelutti, R.E. 1974 How to establish vegetation on high iron-sulphur mine tailings. Canadian Mining Journal, October 1974. pp. 55-58.

Nicholson, Ronald V., Robert W. Gillham, John A. Cherry & Eric J. Reardon. 1989 Reduction of acid generation in mine tailings through the use of moisture-retaining cover layers as oxygen barriers. Canadian Geotechnical Journal 26: 1-8. http://dx.doi.org/10.1139/t89-001

Nicholson, R.V., F.F. Akindunni, R.C. Sydor & R.W. Gillham. 1991. Saturated tailings covers above the water table: the physics and criteria for design. Proceedings Second International Conference on the Abatement of Acidic Drainage, Montréal, September 1991. Vol. I, pp. 443-460.

Parizek, R.R. 1987. Use of waste products to reclaim strip-mined lands. In: Carlson, C.L. & J.H. Swisher (eds.), Innovative Approaches to Mined Land Reclamation, Southern Illinois University Press: Carbondale. pp. 223-281.

Parry, G.D.R & R.M. Bell. 1985. Covering systems. In: Smith, M.A. (Ed.), Contaminated Land: Reclamation and Treatment. Plenum: NY, pp. 113-139.

Peters, T.H. 1984. Rehabilitation of mine tailings: a case of complete ecosystem reconstruction and revegetation of industrially stressed lands in the Sudbury area, Ontario, Canada. In: Sheehan, P.J., G.C. Butler & P. Bordeau, Effects of Pollutants at the Ecosystem Level. Wiley : N.Y. pp. 403-421.

Rauser, W.E. and E.K. Winterhalder. 1985. Evaluation of Copper, Nickel, and Zinc Tolerances in Four Grass Species. Canadian Journal of Botany 63: 58-63. http://dx.doi.org/10.1139/b85-009

Reardon, E.J. & P.M. Moddle. 1985. Suitability of peat as an oxygen interceptor material for the close-out of pyritic uranium tailings: column studies. Uranium 2: 83-110.

Roshon, Roxana D.. 1988. Genecological studies on two populations of *Betula pumila* var. *glandulifera*, with special reference to their ecology and metal tolerance. M.Sc. Thesis, Laurentian University, Sudbury, Ontario. 231 pp..

Spires, A.C. 1975 Studies on the use of overburden soils in facilitating vegetative growth on high sulphide tailings. M.Sc. Thesis, Laurentian University. 151 pp.

Winterhalder, K. 1988. Spatial heterogeneity in an industrially attenuated landscape before and after revegetation. In: M.R.Moss, ed., Landscape Ecology and Management. Polyscience: Montreal. pp. 203-210.

Young, C.A. 1969. The use of vegetation to stabilize mine tailings areas at Copper Cliff. Canadian Mining Journal 90: 43046.