AQUATIC PLANT ESTABLISHMENT ON WATER-COVERED NICKEL TAILINGS[1]

by

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Abstract. Nickel tailings were deposited between 1978 and 1988 in Falconbridge's New Tailings Area located northeast of Sudbury, Ontario, Canada. In 1996, construction of a new dam and dredging split the site into an Upper Terrace (56 ha) and a Lower Terrace (30 ha) to facilitate flooding. Water covers minimize the oxidation of acid generating tailings but some oxidation and release of metals may still occur. The effectiveness of a water cover could be improved by establishing aquatic plants to control tailings resuspension, remove metals from the water column and develop an organic layer to consume oxygen and support sulphate-reducing bacteria. Research was conducted from 1997 to 1999 to evaluate establishing submerged aquatic plants in the New Tailings Area.

In 1998, six submerged aquatic species were introduced into the site using 540 transplant 'sandwiches' constructed by placing shoot biomass between layers of wire mesh. In 1999, aquatic plant distribution was assessed along transects every 100 m across the Lower Terrace. In addition, aboveground biomass was determined for each species using a 0.25 m^2 quadrat placed every 10 m along each transect.

In the Lower Terrace, due to natural invasion, 189 of the 226 sites sampled in 1999 contained aquatic plants. Of the seven species identified, *Potamogeton pusillus* was found at 113 sites (mean cover 49.9% and mean biomass 60.8 g DW/m^2) and *Chara* spp., at 79 sites (mean cover 18.3% and mean biomass 20.6 g DW/m^2). Aquatic plant growth was limited in water less than 0.5 m deep due to wave action and in water greater than 2.0 m deep from suspended solids in the water column that restricted light penetration. In the transplant trials, *Potamogeton richardsonii* was successfully established, but growth of the other species was limited due to the transplant method or site conditions.

Additional Key Words: plant colonization, acid mine drainage, wetlands, reclamation

Introduction

In Canada, water covers are presently considered the best available technology for acid mine drainage prevention and long-term storage of acid generating tailings (Davé *et al.* 1997). There is concern, however, that some oxidation may still occur (Aubé *et al.* 1995). Dissolved oxygen could be transported through the water column to the tailings by diffusion, convection or circulating currents. Tailings resuspension by wave action might expose sulphide particles to dissolved oxygen in the water column (Li *et al.* 1997). If sufficient oxidation of the sulphide particles occurred, the resulting acid generation and metal flux could cause deterioration in the water cover quality.

The establishment of aquatic vegetation and subsequent development of an organic layer can improve the effectiveness of water covers on the flooded tailings. The decomposition of the organic matter by aerobic bacteria should slow the diffusion of oxygen into the tailings and subsequently decrease acid generation. Metals released from the tailings and in the water column could be removed and retained in the sediment by organic complexation or be precipitated as sulphide complexes through the activities of sulphate-

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reducing bacteria. During a drought, an organic layer would act as a sponge preventing oxygen diffusion onto the tailings surface as water levels dropped within a tailings impoundment. Aquatic plants and the associated root mass would control shoreline erosion and prevent tailings resuspension by wave or wind action while providing biological treatment by removing metals and nutrients from the water column. Aquatic plants provide esthetic enhancement and are an important component of an aquatic ecosystem.

With sufficient time, aquatic vegetation will colonize flooded mine tailings. At Rio Algom's Panel Wetland (Elliot Lake, Ontario), uranium tailings that spilled into a small basin in the late 1950's have developed into a natural wetland (Davé 1993). In areas with shallow water cover (0.1 to 0.5 m), cattails, grasses, sedges and sphagnum have formed a dense cover with submerged species in deeper water. In Flin Flon, Manitoba, *Carex* spp., *Podostemun ceratophyllum* Michx. and *Eleocharis* spp. have colonized copper tailings deposited into a shallow lake in 1943 and 1944 (Hamilton and Fraser 1978, Rescan 1990). Kalin and Smith (1987) documented the natural colonization of *Characeae* in abandoned gold tailings ponds in Timmins, Ontario.

Transplanting wetland species into the flooded tailings impoundments can assist the natural colonization process by introducing larger volumes of plant material than would naturally invade the site, and can include species best suited for the site conditions which may not otherwise have naturally invaded. Laurentian University's Elliot Lake Research Field Station conducted transplant trials at Rio Algom's Quirk Waste Management Area. Vegetation islands (10 m^2) consisting of stem, roots and rhizomes of six shoreline species were established on uranium tailings in water depths of 0.3 - 0.6 m. By 1998 the diameters of the islands for most species had increased several hundred per cent (Beckett *et al.* 1999). At Noranda's Brenda Mine (Kelowna, British Columbia), 850 sandwiches (1 m^2) containing a submerged plant mixture of 75% *Elodea canadensis*, 15% *Potamogeton crispus*, 3% *Myriophyllum exalbescens* and 2% *Ceratophyllum demersum* were distributed on copper/molybdenum tailings at water depths ranging from 1 to 4 m. After three years, aquatic vegetation produced weedbeds with a cover varying from 60 to 100% (St-Germain *et al* 1997).

This paper examines the introduction and invasion of submerged macrophytes into flooded nickel tailings at Falconbridge's New Tailings Area. The study objectives were to assess the establishment, growth and spread of submerged aquatic plants in the New Tailings Area and to identify site conditions, water quality or sediment characteristic affecting aquatic growth.

Site Characteristics

The Smelter Complex of Falconbridge Limited is located approximately 15 km northeast of Sudbury, Ontario, Canada. Mining and milling at the Falconbridge site began in the late 1920's and early 1930's and ceased in 1990. The ore milled contained nickel and copper as pentandite and chalcopyrite with pyrrhotite as the main sulphide mineral with varying amounts of magnetite and pyrite.

The New Tailings Area, located about 2.0-km northeast of the Falconbridge Smelter, was utilized for tailings deposition between 1978 and 1988. Until 1985, about 3.2 million tonnes of tailings with an average sulphur content of 7% were deposited. Starting in 1985, low sulphur tailings (1% sulphur) were produced by removing the pyrrhotite and in 1986, coarse material was cycloned off for underground back fill. A dam was constructed across the impoundment to form the Upper Terrace, where the low sulphide slimes were deposited. Approximately 1.1 million tonnes of low sulphide tailings were deposited between 1985 and 1988 (Golder Associates 1997).

Closure work on the New Tailings Area commenced in 1996 with the construction of Dam 1 and Dam 12 down stream of the original dam to facilitate flooding (Figure 1). Dredging to relocate tailings that would be exposed when the terraces were flooded to the design water levels was completed in 1996 on the Lower Terrace and in 1998 on the Upper Terrace. Spring water flows into the Upper Terrace and Lower Terrace, which cover approximately 56 ha and 30 ha respectively. Typical water quality is summarized in Table 1.

In the Upper Terrace, water depths generally ranged between 1 m and 2 m. Shallow areas are located in the South Bay, West Bay and in areas where the dredged tailings were deposited. In between the original Dam 12 and New Dam 12 water depths reached 4 m. In the Lower Terrace at the north end, the water cover on the original tailings reached depths of 0.75 m. At the south end shallow mounds were formed where dredged tailings were deposited, with depths ranging up to 0.5 m between mounds. Deeper areas were located in the middle of the Lower Terrace where the maximum water depth reached 4.5 m.

Table 1. Average surface water quality in the Upper Terrace and Lower Terrace in August and September 1999.

Parameters	Upper Terrace (n=4)	Lower Terrace (n=4)
pH	7.88	7.85
Conductivity (µmhos/cm)	695	638
Alkalinity (mg/L) as $CaCO_3$	44	35
Turbidity (NTU)	1.5	13.5
Total Suspended Solids (mg/L)	1	21
Total Dissolved Solids (mg/L)	529	476
$S0_4^=$ (mg/L)	263	259
Hardness (mg/L) as $CaCO_3$	302	294
B (mg/L)	0.12	0.04
Ca (mg/L)	92.9	91.3
Cu (mg/L)	0.003	0.003
Fe (mg/L)	0.004	0.007
K (mg/L)	10.2	10.2
Mg (mg/L)	17.1	16.1
Mn (mg/L)	0.001	0.001
Na (mg/L)	20.5	16.0
Ni (mg/L)	0.40	0.07
P (mg/L)	0.001	0.003
Zn (mg/L)	0.044	0.008

Methods

Plant material was harvested, in August 1998 from the donor sites by collecting shoot biomass along with roots and rhizomes. *Elodea canadensis* and *Potamogeton richardsonii* were harvested from Robinson Lake (20 km southwest of Falconbridge) while *Potamogeton pusillus, Myriophyllum sibiricum* and *Potamogeton gramineus* were available nearby on Falconbridge property. For each species, 72 mini-sandwiches (0.5 x 0.5 m) were constructed by placing a 5 cm layer of plant biomass between two layers of 2.5 cm mesh chicken wire. The positive buoyancy of the plants made it necessary to add rocks to the mini-sandwiches for additional weight. Edges were folded shut and the middle bound with a plastic tie. An additional 72 large sandwiches (1.0 x 1.0 m) were constructed for *Potamogeton richardsonii.* Sandwiches were placed at two sites in the Upper Terrace and four sites in the Lower Terrace. At each site, three test plots were established in which four sandwiches per species were placed in parallel rows extending 10 m from the shore.

Transplant survival and establishment was visually assessed for the different species following transplanting. In September 1999, 0.25 m^2 (0.5 x 0.5 m) quadrats were established beside *Potamogeton richardsonii* sandwiches at each site and in Robinson Lake. For each species present in the quadrats, percent cover was estimated and the biomass was harvested and bagged. A sediment core was collected from the center of each quadrat by inserting a plexiglas core tube (6.5 cm internal diameter) into the sediment to a depth of approximately 0.15 m. The tube was capped, raised to the surface and the sample retrieved into a polyethylene jar. Plant tissue and sediment samples were stored in a cooler and transported to the laboratory. In July 2000, *Potamogeton richardsonii* spread rate was assessed using the small sandwiches established farthest from the shoreline in each test plot. The distance that the plants had spread to the north, south, east and west of the sandwich was measured.

The abundance of submerged aquatic plants was assessed in August 1999. Ten transects were placed 100 m apart across the Lower Terrace and quadrats (0.25 m^2) were established every 10 m along each transect. In each quadrat, water depth was measured and for each species percentage cover was estimated, biomass harvested, bagged and stored in a cooler until transported to the laboratory. This work was conducted in shallow areas by snorkeling and in deeper areas (>1.0 m) by SCUBA.

In the laboratory, plant samples were washed with distilled water, dead plant material and debris were removed, the number of stems was counted and plants were air-dried. Samples were oven dried at 70^{0}C to a consistent weight. Nitrogen in the plant tissue was determined by the Kjeldahl method. For the other elements, samples were ashed, digested and analyzed using inductive couple plasma atomic emission spectrophotometry (ICP-AES). U.S. National Institute of Standards and Technology certified reference material (peach leaves SMR 1547) was digested with the analytical run.

Statistical analyses were performed using statistical analysis software SPSS. Data sets were $\log_{10}$ transformed when required to meet assumptions of normality and homogeneity of variance. Differences in biomass and nutrient concentrations were tested by one-way analysis of variance. Turkey's multiple range test was used to differentiate means where appropriate. A probability level of ≤ 0.05 was used in all comparisons. Stepwise multiple regression was performed on *Potamogeton pusillus* shoot nutrients to determine variables affecting biomass production. The relationship between sediment nutrients and shoot nutrient concentrations was investigated using Pearson correlation coefficients.

Results

Transect Survey

Six species of submerged aquatic plants were found in 189 of 226 quadrates. Water reached depths of 2.25 m but 80% of the quadrats were less than a 1 m deep. Biomass production in water <0.25 m was 2.31 g/m^2. Production increased with depth and peaked at 162.6 g/m^2 between 1.0 to 1.25 m. No aquatic plants were observed at depths greater than 2 m (Table 2).

Table 2. Mean biomass collected at different depths along the Lower Terrace transects.

Depth m	Plots	Plots without Vegetation	Biomass g/m^2
<0.25	16	8	2.31
0.26 - 0.50	49	11	22.2
0.51 - 0.75	84	10	35.3
0.76 - 1.00	27	3	48.3
1.01 - 1.25	9	0	162.6
1.26 - 1.50	7	1	71.2
1.51 - 1.75	17	0	52.4
1.76 - 2.00	6	0	43.2
2.00 - 2.25	3	3	0

Potamogeton pusillus, the most abundant species was found in 113 quadrats with a mean cover of 49.9% and mean biomass of 60.8 g/m^2. *Potamogeton pusillus* biomass was highest (307.6 g/m^2) in the south end of the Lower Terrace where extensive weedbeds had formed except on the tailings mounds created by dredging. Establishment of *Potamogeton pusillus* had begun on the original tailings but only below Dam 12 was biomass production similar to levels observed at the south end of the Lower Terrace.

Chara spp. was present in 79 quadrats with a mean cover of 18.2% and a mean biomass of 20.5 g/m^2. The majority of sites were located on the original tailings with the largest patch located at the north end where biomass reached 230.8 g/m^2. Water from Fault Lake Spring, which contains extensive beds of *Chara* spp. flows into the Lower Terrace at the north end.

The other species identified were found on a limited number of quadrats or had low biomass production. *Vallisneria americana* was found in 68 quadrats primarily on the original tailings, however, mean biomass production was only 0.24 g/m^2. *Eleocharis acicularis* was present in seven quadrats, all located on the original tailings below Dam 12, and biomass ranged from 2.0 to 192.0 g/m^2. Nine quadrats contained *Potamogeton friesii* of which four quadrats were located at the northwest corner below Dam 12. At two sites biomass was 72.8 and 83.0 g/m^2, but at the others below 10 g/m^2.

During the survey *Polygonum amphibium* and *Sparganium fluctuans* were observed in the Lower Terrace but were not located in the quadrats. Along the shoreline emergent aquatic plants (*Typha latifolia*), along with wetland grasses (*Phragmites australis, Glyceria canadensis*), sedges (*Carex scoparia, Scirpus acutus, Scirpus torreyi*) and rushes (*Juncus effusus, Juncus brevicaudatus*) had started to colonize. The major species observed were *Typha latifolia, Scirpus acutus* and *Phragmites australis.*

Stepwise multiple regression analysis was performed using *Potamogeton pusillus* biomass (both transects and sandwich quadrats) as the dependent variable and nutrient concentrations and water depth as independent variables. Sixty five percent of the variance in *Potamogeton pusillus* biomass could be explained by five variables. Increases in boron and potassium concentrations explained 41.6% and 11.8% percent of the variance, while decreases in Mg, S and Ni explained 9.6%, 4.0% and 2.0% of the variance, respectively (Table 3).

Table 3. Stepwise multiple regression of *P. pusillus* shoot biomass to shoot nutrient concentrations.

Variable	B	SE B	MR	ΔR^2
B	1.719	.356	.649	41.640
K	5.255	.619	.737	11.757
Mg	-1.571	.434	.803	9.593
S	-3.016	.617	.844	4.013
Ni	-.589	.200	.859	1.962
Constant	-7.623	.765		

Transplant Trials

When the sandwiches were evaluated in September 1998, all five species survived transplanting. *Myriophyllum sibiricum* had produced new shoots that covered the sandwiches. *Potamogeton pusillus, Potamogeton richardsonii* and *Elodea canadensis* produced fewer new shoots, while *Potamogeton gramineus* growth was limited.

Visual evaluation in June 1999 indicated that *Potamogeton richardsonii* had spread up to 0.5 m from the sandwiches. New growth of *Potamogeton pusillus* was observed on the sandwiches; however, spread could not be verified due to the abundance of this species within the Lower Terrace. For *Myriophyllum sibiricum* and *Elodea canadensis* most plant material had disappeared and few shoots were observed. *Potamogeton gramineus* growth was limited except at one site in the Upper Terrace where growth rates were similar to those observed for *Potamogeton richardsonii.*

The mean biomass of *Potamogeton richardsonii* harvested in September 1999 from the Upper Terrace and the Lower Terrace were not significantly different but were approximately a quarter of the biomass harvested from Robinson Lake. However, mean stem numbers and mean cover in the Lower Terrace were significantly higher than in the Upper Terrace indicating that in the Upper Terrace *Potamogeton richardsonii* had produced longer or thicker stems (Table 4).

Tissue nutrients in *P. richardsonii* from the Upper and Lower Terrace were significantly higher in S, K, Ca, Al, Zn and Ni while significantly lower in Na and B than plants from Robinson Lake. Plants from the Upper Terrace had significantly higher Na, B, Mn and Ni concentrations and significantly lower N, P, Mg, Fe and Cu concentrations than plants from the Lower Terrace while S, K, Ca, Al and Zn concentrations were not significantly different (Table 4).

Biomass harvested for *Potamogeton pusillus* and *Chara* spp. was not significantly different from *Potamogeton richardsonii* biomass; however, percent cover was significantly different (Table 5). Comparision of tissue nutrients between species indicated that in *Potamogeton richardsonii* Mg, Cu and Zn concentrations were significantly higher while S, K, Na and B were significantly lower than in *Potamogeton pusillus.* *Chara* spp. had significantly higher concentrations of Ca, Fe and Mn and significantly lower concentrations of N, S, P, K and Na compared to *Potamogeton richardsonii* or *Potamogeton pusillus.* Concentrations of Al and Ni were not significantly different between species.

Table 4. Mean vegetation estimates and nutrients measured in aboveground parts of *P. richardsonii* from three sites in September 1999 (significant differences indicated by letter superscripts).

Parameters	Upper Terrace (n=16)	Lower Terrace (n=37)	Robinson Lake (n=9)
Biomass (g/m^2)	18.2 ^{b}	17.4 ^{b}	69.8 ^{a}
Stems/m^2	108 ^{c}	150 ^{b}	368 ^{a}
% Cover	9.7 ^{b}	14.3 ^{a}	n.a.
N (%)	1.89 ^{b}	2.65 ^{a}	1.58 ^{b}
S (%)	1.27 ^{a}	1.18 ^{a}	0.94 ^{b}
P (%)*	0.18 ^{b}	0.22 ^{a}	0.19 ^{b}
K (%)	2.06 ^{a}	1.97 ^{a}	0.97 ^{b}
Mg (%)	0.75 ^{b}	0.82 ^{a}	0.70 ^{b}
Ca (%)	1.80 ^{a}	1.73 ^{a}	1.28 ^{b}
Na (%)*	0.30 ^{b}	0.22 ^{c}	0.56 ^{a}
Fe (μg/g)*	1262 ^{b}	2340 ^{a}	445.3 ^{b}
Al (μg/g)*	886.0 ^{a}	1451 ^{a}	453.2 ^{b}
Mn (μg/g)	382.9 ^{a}	221.5 ^{b}	381.7 ^{a}
B (μg/g)*	19.6 ^{b}	18.9 ^{b}	20.9 ^{a}
Cu (μg/g)	45.4 ^{b}	59.8 ^{a}	67.1 ^{a}
Zn(μg/g)*	100.7 ^{a}	97.6 ^{a}	61.2 ^{b}
Ni (μg/g)	4250 ^{a}	1819 ^{b}	291.7 ^{c}

*Analysis on $\log_{10}$ transformed data

Table 5. Mean vegetation estimates and nutrients in aboveground parts of species from the Lower Terrace in September 1999 (significant differences indicated by letter superscripts).

Parameters	*P. richardsonii* (n=37)	*P. pusillus* (n=27)	*Chara spp.* (n=36
Biomass (g/m^2)	17.4 ^{a}	17.6 ^{a}	18.3 ^{a}
% Cover	14.3 ^{c}	33.4 ^{a}	24.6 ^{b}
N (%)	2.65 ^{a}	2.51 ^{a}	1.33 ^{b}
S (%)	1.18 ^{b}	1.52 ^{a}	0.96 ^{c}
P (%)	0.22 ^{a}	0.22 ^{a}	0.12 ^{b}
K (%)	1.97 ^{b}	2.46 ^{a}	0.85 ^{c}
Mg (%)	0.82 ^{a}	0.53 ^{c}	0.64 ^{b}
Ca (%)	1.73 ^{b}	1.76 ^{b}	16.55 ^{a}
Na (%)*	0.22 ^{b}	0.78 ^{a}	0.07 ^{c}
Fe (μg/g)*	2340 ^{b}	2857 ^{b}	3811 ^{a}
Al (μg/g)*	1451 ^{a}	1161 ^{a}	1550 ^{a}
Mn (μg/g)*	222 ^{b}	272 ^{b}	360 ^{a}
B (μg/g)	18.9 ^{b}	290.0 ^{a}	30.6 ^{b}
Cu (μg/g)	59.8 ^{a}	39.6 ^{b}	56.8 ^{a}
Zn (μg/g)*	97.6 ^{a}	67.7 ^{b}	40.0 ^{b}
Ni (μg/g)	1819 ^{a}	1771 ^{a}	1874 ^{a}

*Analysis on $\log_{10}$ transformed data.

Evaluations in July 2000 indicated that at Sites 4, 5 and 6, *Potamogeton richardsonii* had spread by rhizomes up to 5 m from the sandwiches and the area cover around the sandwiches ranged from 3.3 to 15.0 m^2 (Table 6). At site 3 (shallow with sandy sediments), *Potamogeton richardsonii*, which was present in 1999, was not observed in 2000.

Table 6. Spread and area covered by *P. richardsonii* in July 2000 from sandwiches established in the 1998 Transplant Trials.

Site	Average distance from Sandwich (m)	Area covered (m^2)
4	2.48	13.9
4	3.75	15.0
4	2.95	11.8
5	2.08	8.3
5	0.83	3.3
5	3.1	12.4
6	2.8	11.2
6	1.6	6.4

Discussion

Many factors influence aquatic plant abundance and distribution at a site. Light availability, sediment and water column nutrient status, sediment texture, along with wind and wave action, are important parameters. These are interrelated and interact with lake morphology (size, shape, depth, bottom slope) to determine colonization and zonation of the submerged macrophytes.

Physical Factors

One of the most important limiting resources for submerged macrophytes is light (Spence 1982). Aquatic plants require light for growth and thus the maximum depth of plant growth is regulated by light availability. Chambers and Kalff (1985) observed that in lakes with Secchi depths of less than 1 m, insufficient light prevented growth. Plant establishment was not observed in the Lower Terrace at depths below 2.0 m, which was approximately two times the Secchi disk readings measured in 1998. Water sampling and the sediment traps indicate high-suspended solid levels in the Lower Terrace due to shoreline erosion and mixing of bottom sediments. Suspended solid levels were highest at the North end of the Lower Terrace due to erosion from tailings banks left along the shoreline when dredging ended.

Surface area and shape influence the effect wind can have on wave size and current strength. Large bodies of water typically have longer fetches (areas open to the prevailing winds) resulting in large waves and stronger currents. In exposed areas wave action prevents plants from establishing; therefore, aquatic plant establishment tends to be higher in sheltered areas (Foote and Kadlec 1988). Wave action sorts the bottom sediments leaving coarse material in shallow areas and depositing the fine material in deeper areas. Sediments with a high sand content tend to have low aquatic plant growth due to nutrient deficiencies (Barko *et al.* 1991) and some species show a clear preference for a particular substrate texture (Pip 1979).

Biomass production in the shallow areas (<0.25 m) of the Lower Terrace was low and only half the quadrats contained aquatic plants. These sites were either along the shoreline where erosion by storm events and wave action resulted in sediments with a high sand content or were dredged tailings mounds that contained 90 % sand. Wave action removed plant biomass from the transplant sandwiches and inhibited plant establishment by covering sandwiches with sediment. On the original tailings in the Lower Terrace aquatic plant establishment was greatest in the sheltered areas below Dam 12 and the north end of the Lower Terrace.

As water depth increased, the type of aquatic plant and the productivity of the species changed. In Robinson Lake (the donor site), *Potamogeton richardsonii* was found in a zone extending 20 to 25 m from shore where water depth ranged from 0.2 to 0.75 m. In deeper water (> 1.0 m) large beds of *Elodea canadensis* were observed. In McFarland Lake (also in Sudbury) *Potamogeton richardsonii* was found in shallow areas followed by *Myriophyllum sibiricum* in deeper water (>1.0 m). In the transplant program, sandwiches were established at depths ranging from 0.15 to 0.75 m, which was too shallow to successfully establish *Elodea canadensis* and *Myriophyllum sibiricum*.

Chemical Factors

Rooted submerged aquatic plants absorb nutrients essential for growth both through their leaves in the water column and through their roots in the sediment. Dissolved products of the relatively abundant salts Ca, Mg, Na, K, Cl and $SO_4^=$ are primarily acquired from the water column. N, P, Fe, Mn along with micronutrients are primarily acquired from the sediment, as these elements are usually present in low concentrations in the water column (Barko *et al.* 1991). However, the uptake of nutrients will vary depending on site conditions. Under oligotrophic conditions, plants would extract most of the nutrients from the sediment with subsequent transport to the shoots. Under eutrophic conditions, passive or active transport from the water column can result in luxury uptake of nutrients above the levels required to support growth with metals being bioaccumulated to concentrations many times greater than the levels surrounding the plant (Hutchinson 1975).

Initially, we hypothesized that nitrogen and phosphorus deficiencies would restrict aquatic plant growth in the New Tailings Impoundment because these elements are most likely to be limiting in natural systems (Barko *et al.* 1991). However, this does not appear to be the case in the New Tailings Impoundment. In *Potamogeton pusillus* and *Potamogeton richardsonii* tissue nitrogen and phosphorus were above 1.3% and 0.13%, which are reported as critical concentrations in water plants (Hutchinson 1975). Nitrogen and phosphorus levels in *Potamogeton richardsonii* from the Lower Terrace and Upper Terrace were similar or significantly higher than levels in *Potamogeton richardsonii* from Robinson Lake.

In the stepwise multiple regression analysis 40% of the variance in *Potamogeton pusillus* biomass could be explained by increasing boron concentrations. In the sandwich quadrats, boron concentrations in *Potamogeton pusillus* were 290.0 μg/g compared to 18.9 μg/g in *Potamogeton richardsonii* and 30.6 μg/g in *Chara* spp. It appears that *Potamogeton pusillus* has a higher boron requirement than the other species. Boron concentrations in the sediment were below 1.0 ppm and in the water column ranged from 0.06 to 0.12 mg/L.

Increases in potassium concentrations explained 11.7% of the variance in *Potamogeton pusillus* biomass while decreases in magnesium and sulphur explained 9.6% and 4.01% of the variance. Potassium, magnesium and sulphur primarily acquired from the water column and the levels in the Lower Terrace are above levels considered high (Smart and Barko 1988). Luxury uptake of these nutrients could be occurring and nutrient levels may reflect differences in nutrient concentrations in the Lower Terrace rather than potassium deficiencies or magnesium and sulphate toxicities.

When sediment nutrient concentrations were correlated with the nutrient concentrations of *Potamogeton pusillus, Potamogeton richardsonii* and *Chara* spp., only calcium, iron and magnesium in *Chara* spp. were correlated. This general lack of correlation between tissue and sediment nutrient concentration is partially due to the effects of the water column on tissue nutrient concentrations and the fact that total sediment nutrients concentrations do not take into account bioavaibility of the nutrients. Additionally, the growth form of the plant will influence nutrient concentrations. Jackson and Kalff (1993) observed that understory plants had a higher metal content than canopy forming species for a given sediment metal concentration. Significant differences were observed in tissue nutrient concentrations for most elements in *Chara* (algae), *Potamogeton pusillus* (canopy species) and *Potamogeton richardsonii* (understory species) in the study.

Species Selection

Flooded mine tailings impoundments vary in size, shape and water depth. The physical characteristics of the tailings impoundment influence the type of aquatic plant that can be established. Emergent plants grow on water-saturated or submerged soil and have aerial, mature leaves above the water and are suitable for a shallow shoreline. Nutrients for plant growth are taken from the sediment. Common emergent plants include reeds (*Phragmites* spp.), bulrushes (*Scripus* spp.) and cattails (*Typha* spp.). Floating-leaved aquatic plants such as waterlilies (*Nymphaea* spp.), yellow pond lily (*Nuphar* spp.) and watershield (*Brasenia* spp.) are rooted in the sediment and have leaves that float on the surface. These later species tend to be found in sheltered areas as the leaves and stems can be ravaged by wind and wave action. Submerged aquatic plants grow mainly underwater although some species will produce leaves that float on the surface. Nutrient uptake is from the sediment and water column. This group includes muskgrass (*Chara* spp.), which is a macroalgea, pondweed (*Potamogeton* spp.), waterweed (*Elodea* spp.), and milfoil (*Myriophyllum* spp.). Submerged aquatic plants were selected for the transplant trials at Falconbridge because they tolerate a range of water depths and spread rapidly by rhizomes or fragments.

The submerged aquatic plants used in this program were selected because they were available locally or had been utilized successfully in other transplant programs. The local availability of the species is important from a practical aspect and also helps to avoid the risk of introducing a nuisance species to the area. However, any species has the potential to become a nuisance if the conditions and site habitat are appropriate. Falter and Naskali (1974) found that in the Snake and Columbia River drainage basin (U.S.) 15 taxa including *Elodea canadensis*, *Potamogeton pusillus*, *Myriophyllum sibiricum* and *Potamogeton richardsonii* were responsible for the majority of the nuisance plant occurrences. However, 95% of the species identified in their study had been reported as a nuisance species at least once. Aquatic plants most suitable for establishment in a flooded tailings impoundment have high transplant survival and aggressive growth habits that result in rapid rhizome growth and new shoot production.

Conclusions

Submerged aquatic plants can be successfully established on Falconbridge nickel tailings at the New Tailings Impoundment. *Potamogeton pusillus* and *Chara* spp. had naturally invaded into the Lower Terrace and formed extensive weedbeds. *Potamogeton richardsonii* and *Potamogeton pusillus* were successfully transplanted and established in the Upper Terrace and Lower Terrace.

Plant establishment in the New Tailings Area was influenced by several factors. In shallow areas aquatic plant establishment was inhibited by wind and wave action along with nutrient deficiencies in areas with a high sand content. Aquatic plant establishment was restricted to depths of less than 2 m because of suspended solids that restricted light penetration. However, nutrient deficiencies did not appear to have a major role in influencing plant growth. Dissolved products of relatively abundant salts: Ca, Mg, Na, K, Cl and $S0_4^=$sulphate, which are primarily acquired by aquatic plants from the water column, are at levels in the Upper and Lower Terraces that would be considered high. Nutrient levels were similar or significantly higher in *Potamogeton richardsonii* tissue from the Lower Terrace compared to the donor site.

Aquatic plants introduced in the transplant trials survived the transplanting process but *Elodea canadensis*, *Potamogeton gramineus* and *Myriophyllum sibiricum* did not survive long term. It appears water depth was the main factor affecting the survival of these species. This illustrates the need to conduct transplant trials to assess plant growth and establishment before full-scale transplanting programs are undertaken at any site. Trials should identify site conditions (pH, turbidity and nutrient deficiencies) that could restrict plant growth and allow remediation methods to be developed to alleviate these conditions. The most practical and cost effective transplant method and the plant species most suitable for use should be determined through these trials.

When decommissioning existing tailings impoundments or designing new tailings facilities consideration should be given to improving the site potential to support wetland plants. Ponds can be designed with a range of water depths that would be suitable for shoreline, floating and submerged plant species. Shorelines could be enhanced by creating a series of bays that would help protect plants from wave action and provide different site conditions along the shoreline. The creation of islands within the tailings impoundment would reduce fetch, improve esthetic appearance and provide wildlife habitat.

Regular surveys of flooded tailings impoundments should document the development and long-term changes in the aquatic macrophyte community. Growth rates, bioaccumulation of metals, and decomposition rates for the various aquatic plant species on flooded tailings need to be studied. In the sediment layer, research is required on the decomposition rate of organic matter by aerobic bacteria and how effectively metals from the tailings or water column are retained in the sediment layer by organic complexation or precipitated as sulphide complexes through the activities of sulphate-reducing bacteria. This research will help increase the understanding of tailings restoration and wetland development on flooded mine tailings.

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