MINELAND RECLAMATION USING OFFICE WASTE PAPER DE-INKING RESIDUE[1]

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Abstract: Pulp facilities which recycle office waste paper generate large amounts of waste by-products in the process of producing high-grade pulp. The paper-like residue, called de-inking residue, was evaluated for use in the revegetation of coarse taconite tailings in northeastern Minnesota. Minnesota Mineland Reclamation Rules specify that a 90 percent vegetative cover shall be established on tailings after three growing seasons; however, the 90 percent cover requirement on coarse tailings has not been consistently achieved using standard reclamation practices. Research plots were established in 1992 at the Eveleth Mines Fairlane Plant utilizing a randomized block design using five levels of de-inking residue, five levels of fertilization, and two plant mixes on 2.5- by 4.0-m plots. Lysimeters were installed to monitor changes in sub-surface water quality. Vegetative cover was measured at two sampling periods each in 1992 and 1993. Fertilization and de-inking residue amendments had significant effects on the vegetative cover of introduced and native plant species. Vegetative cover for introduced species increased from no cover to 49 percent at the end of the first growing season, to 90 percent at the end of the second growing season on tailings fertilized at the highest level and amended with residue at 22.4 kg ha^{-1}. At the same fertilizer and de-inking residue rate, vegetative cover for native plants increased from no cover to 7 percent at the end of the first growing season, to 69 percent at the end of the second growing season.

Additional Key Words: Coarse Taconite Tailings, De-inking Residue

Introduction

Mandatory paper recycling programs at the state level have promoted the development and construction of processing facilities that use recycled paper to produce pulp. As a by-product of this paper recycling process, a large amount (150 wet metric tons per day) of paper-like residue can be generated at a facility. The paper-like residue, called de-inking sludge or residue, is generated as a result of various mechanical and chemical processes used to remove contaminants from recycled paper. In many operations, de-inking residue is disposed of by landfilling, but in Minnesota, both the state and a private company are interested in reusing the residue in a beneficial manner. One potential beneficial use of de-inking residue may be to aid in the restoration of vegetation on land used for the disposal of coarse taconite tailings.

Coarse tailings are difficult to vegetate because of their inherently poor physical, chemical, and biological properties. Coarse tailings are dark colored sand-sized particles. The tailings tend to absorb and retain heat, resulting in high temperatures at the surface during the summer months. Coarse tailings are also difficult to vegetate because of: high pH; low organic carbon and organic matter contents; low cation exchange capacity (CEC); limited ability to hold moisture; and inherent lack of nutrients essential for plant growth.

The Minnesota Department of Natural Resources (MDNR) Mineland Reclamation Rules specify that a "90 percent ground cover shall exist on all areas after three growing seasons following the point when the facility is no longer used, except on slopes which face south and west." Such sloped areas shall attain 90 percent ground cover within five growing seasons (Minnesota Department of Natural Resources 1980).

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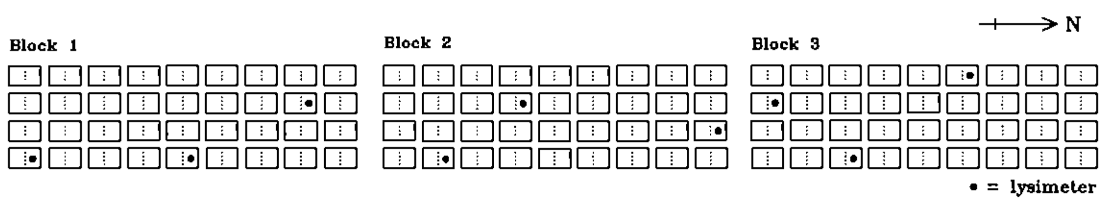
The U.S. Bureau of Mines (USBM) has established research plots on coarse tailings using organic amendments at several locations in northeastern Minnesota, including Eveleth Mines. The research program of the USBM was established because standard methods of revegetation have not been successful in vegetating coarse taconite tailings (Norland 1993; Norland, Veith, and Dewar 1993; Melchert et al. 1994). Many dams and dikes constructed using coarse tailings have only attained a 40 percent to 60 percent plant cover after three years (Shetron and Duffeck 1970; Dewar 1987). In northeastern Minnesota, there are an estimated 10,125 ha of active tailings basins that will need to be reclaimed when the basins are no longer used (Norland et al. 1991).

Northeastern Minnesota is characterized by harsh climatic conditions; short, warm summers and long, cold, snowy winters. The average annual precipitation (Hibbing) is 640 mm per year. The average annual air temperature is 3°C. The summer consists of approximately 110 frost-free days and the seasonal temperature varies from -38°C to 33°C.

The objectives of this two-year study were to determine: 1) the optimum application rates of de-inking residue, with and without fertilizer, in an attempt to achieve a 90 percent vegetative cover; and 2) the environmental impacts of de-inking residue, with and without fertilizer, on sub-surface water quality.

Materials and Methods

In May 1992, 108 plots were established at the Eveleth Mines Fairlane Plant near Forbes, Minnesota, on coarse taconite tailings. The plots were arranged in a randomized block design (Figure 1). The original experimental design included five levels of de-inking residue, three levels of fertilization (changed later to five levels), and two types of vegetation. The location of treatments were randomly assigned to each 2.5- by 4.0-m plot. The levels of de-inking residue were 0, 22.4, 44.8, 89.7, and 179.3 Mg ha^{-1} on a dry weight basis. Inorganic fertilizer was initially applied at 0, 224, and 448 kg ha^{-1} of granular diammonium phosphate (18-46-0). The fertilizer rate 448 kg ha^{-1} of 18-46-0 is routinely used in the revegetation of coarse tailings (Norland, Veith, and Dewar 1991).



Residue Application Rates Mg ha^{-1}	Actual Levels of Applied N and P_2O_5: N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	Seed Mix: Native	Introduced
0	0	0	round-headed bush clover	buckwheat
22.4	40	103	Canada wild rye	alfalfa
44.8	90	202	kalm's brome	smooth brome
89.7	81	206	big bluestem	perennial rye
179.3	179	402	little bluestem	red fescue

All applications on a dry wt. basis

Plots mulched with 4.48 Mg ha^{-1} straw

Figure 1. General plot layout at Eveleth Mines.

De-inking residue was obtained from a paper recycling facility in Illinois. Five composite samples of residue were collected and analyzed for moisture and nutrient content. Five composite samples of coarse tailings to a depth of 15 cm were randomly collected using a 3 ¼ in bucket auger before treatments were applied.

De-inking residue was weighed in the field in containers using a 50 kg hanging scale and the residue was applied to each plot at the experimental rate. After spreading residue uniformly onto plots with a hand rake, fertilizer was broadcast onto the surface and all materials were incorporated by rototilling to a depth of 15 cm. After rototilling, the plots were raked as smooth as possible and broadcast seeded by hand. The plots were lightly raked to incorporate seed. Straw mulch was applied at 4.48 Mg ha^{-1} and plastic netting was placed over the mulch and staked. A 1.8 m high fence was erected around the study area.

Plant species and associated seeding rates used are shown in Table 1. The introduced plant species mix, which is routinely used in the revegetation of coarse tailings, included smooth bromegrass (*Bromus inermis*), red fescue (*Festuca rubra*), perennial ryegrass (*Lolium perenne*), alfalfa (*Medicago sativa*), and buckwheat (*Fagopyrum esculentum*). Native species were also evaluated because the introduced species commonly used have not been consistently successful in achieving a 90 percent vegetative cover. The native species mix included big bluestem (*Andropogon gerardii*), little bluestem (*Schizachyrium scoparium*), kalm's brome (*Bromus kalmii*), Canada wild rye (*Elymus canadensis*), and bush clover (*Lespedeza capitata*). The legumes in both seed mixes were inoculated.

Table 1. Species and seeding rates used on coarse tailings, based on Pure Live Seed (PLS).

	PLS Seeding Rate	
Native Species	**kg ha^{-1}**	**lb ac^{-1}**
Big bluestem (*Andropogon gerardii*)	5.1	4.6
Little bluestem (*Schizachyrium scoparium*)	3.9	3.5
Kalm's brome (*Bromus kalmii*)	3.4	3.0
Canada wild rye (*Elymus canadensis*)	1.6	1.4
Bush clover (*Lespedeza capitata*)	2.6	2.3
Introduced Species		
Smooth bromegrass (*Bromus inermis*)	11.5	10.3
Red fescue (*Festuca rubra*)	6.8	6.1
Perennial ryegrass (*Lolium perenne*)	5.4	4.9
Alfalfa (*Medicago sativa*)	7.1	6.4
Buckwheat (*Fagopyrum esculentum*)	18.6	16.5

Nine suction-cup lysimeters were installed at a depth of 122 cm below the surface. The location of lysimeters are identified on Figure 1. Approximately 10 cm of a silica flour slurry was placed in the bottom of each borehole and the porous ceramic cup was embedded into the slurry. The annular space was backfilled with tailings in lifts of 15 cm and compacted using a small diameter rod. Water samples were collected monthly from lysimeters in June, July, August, and September 1992, and in April, June, August, and September 1993.

In July 1992, additional fertilizer was surface applied to only the south half of each fertilized plot because: 1) poor plant growth was observed, and 2) to maintain the integrity of the original experimental design. It was suspected at that time that less than expected plant growth could be due to inadequate levels of nitrogen and phosphorus due to cool, wet conditions that occurred during the period of vegetative establishment in 1992. On plots initially fertilized with 224 kg ha^{-1} of 18-46-0, additional fertilizer using 37-0-0 and 0-46-0 was applied to one half of each plot resulting in a total application rate of 90 kg ha^{-1} of actual nitrogen and 202 kg ha^{-1} of actual P_2O_5. On plots originally fertilized with 448 kg ha^{-1} of 18-46-0, additional fertilizer using 37-0-0 and 0-46-0 was applied to one half of each plot resulting in a total application rate of 179 kg ha^{-1} of actual nitrogen and 402 kg ha^{-1} of actual P_2O_5. Subsequent vegetative measurements were completed on all divided plots after July 1992.

A cover-point optical projection device was used to determine percent (absolute) vegetative cover in July and September, both in 1992 and 1993. The cover-point optical projection device was mounted on a 1 m long bar that had ten stops along the bar at 10 cm intervals. The percent vegetative cover was determined by looking through the eyepiece and recording hits and misses of vegetation using the fine cross hairs within the optics for each point on the bar. Three transects were made across each plot for a total of 30 point-intercept cover sampling points.

Two-way analysis of variance using the general linear models procedure in SAS (SAS Institute, Inc. 1988) was used to evaluate differences in percent vegetative cover for the main effects of de-inking residue and fertilizer. Contrast statements were used to determine differences among the vegetative cover estimates at the 0.05 significance level. The statistical analysis was done separately for introduced and native species for each sampling period.

Results and Discussion

Coarse Tailings

The chemical properties of coarse tailings are shown in Table 2. The analysis of coarse tailings document the inherent poor chemical characteristics that impact the establishment and growth of vegetation at Eveleth Mines. The pH of coarse tailings was 8.7, similar to the pH on adjacent USBM plots (Norland, Veith, and Dewar 1991). Coarse tailings did not contain high soluble salt concentrations, as shown by a low mean conductivity, that would impair plant growth. Coarse tailings had low levels of organic matter and organic carbon. The lack of organic matter severely limits the ability of the tailings to supply nitrogen, phosphorus, sulfur, and micronutrients to growing vegetation.

The CEC of coarse tailings was low, 2.0 meq 100 g^{-1}, because of its high silica content, large particle size, lack of clay and silt-sized particles, and lack of organic matter. The low CEC and organic matter content of coarse tailings severely limits the ability of tailings to retain both available water and nutrients for plant growth. The levels of nitrogen and phosphorus in coarse tailings were low, as found on adjacent USBM plots (Norland, Veith, and Dewar 1991). The total concentration of potassium in tailings suggests that this macronutrient is at a high level. However, coarse tailings have insufficient levels of most nutrients, including nitrogen, phosphorus, and sulfur for plant growth. Micronutrient levels in coarse tailings were low as compared to common mineral soils in Minnesota (Pierce 1980).

De-inking Residue

De-inking residue is composed of numerous contaminants such as clay, ink, calcium carbonate, and damaged wood fibers, removed from office paper to produce a premium grade pulp. Trace amounts of other contaminants may be present, including dioxin and furan, depending upon the composition of the recycled paper contained in the incoming paper waste stream.

De-inking residue had a moisture content of 67 percent, a pH of 8.2, and an organic carbon content of 26 percent (Table 3). The residue had a low level of nitrogen and a high carbon to nitrogen (C:N) ratio, 123:1. This C:N ratio indicates that the residue has a very low nitrogen content relative to its carbon content.

Table 2. Chemical characteristics of coarse taconite tailings.

Properties	Mean[1]	S.D.[2]
pH	8.7	0.1
Organic Matter (%)	0.96	0.11
Total Organic Carbon (%)	1	0.05
Total Sulfur (%)	0.04	0.02
Sulfate-Sulfur (mg kg^{-1})	13	10
Total Kjeldahl Nitrogen (%)	0.01	0.00
Nitrate-Nitrogen (mg kg^{-1})	0.6	0.3
Ammonium-Nitrogen (mg kg^{-1})	6.4	2.6
Phosphorus, Olsen-P (mg kg^{-1})	1.4	0.5
Boron (mg kg^{-1})	0.1	0.00
C:N Ratio	98	5
CEC (meq 100 g^{-1})	2.0	0.1
Conductivity (mmhos cm^{-1})	0.5	0.3
Extractable DTPA Concentrations (mg kg^{-1})		
Copper	0.14	0.06
Zinc	0.13	0.06
Manganese	16.11	1.64
Cadmium	<0.02	
Chromium	0.01	0.02
Nickel	0.12	0.03
Lead	0.45	0.24
Total Elemental Concentrations (mg kg^{-1})		
Potassium	537.67	36.92
Calcium	8364.83	1161.95
Magnesium	8487.05	645.03
Sodium	93.71	39.01
Aluminum	1456.18	82.67
Iron	71186.85	7106.09
Manganese	3489.04	469.74
Zinc	12.42	1.51
Copper	4.05	0.54
Boron	17.99	1.33
Lead	25.90	2.89
Nickel	8.88	1.22
Chromium	8.74	0.49
Cadmium	7.86	0.75

[1]Mean of five replicates.
[2]S.D. = standard deviation.

The levels of phosphorus and potassium in de-inking residue were low. De-inking residue does not provide a significant amount of macronutrients to vegetation when applied to coarse tailings. Total carbonate content was 18.1 percent and the calcium content was 6.9 percent. Calcium carbonate, a compound removed during the re-pulping process, becomes a component of de-inking residue. De-inking residue had a mean chloride concentration of 287.6 mg kg^{-1}. The CEC of de-inking residue, 8 meq 100 g^{-1}, is low due to the contribution of kaolinite clay and wood fiber in the residue.

The concentrations of cadmium, chromium, copper, lead, nickel, and zinc in de-inking residue were compared to the "ceiling concentrations" identified in the Environmental Protection Agency's (EPA) Standards for the Use or Disposal of Sewage Sludge (Environmental Protection Agency 1993), shown in Table 4. A comparison of the metal concentrations indicate that de-inking residue contains less than 1 percent of the ceiling concentrations allowed in municipal sewage sludge that can be land applied.

Water Analysis

No statistical analysis of the lysimeter water quality data was completed because of the lack of replications, but some general statements can be made about the impacts of de-inking residue on the levels of boron and chloride in sub-surface water at a depth of 122 cm. The Minnesota Department of Health (MDH) has established water quality standards for potable water supplies (Minnesota Department of Health 1991). The standards, known as Maximum Contaminant Levels (MCL) for secondary contaminants, include numerical limits for boron and chloride.

Table 3. Chemical characteristics of de-inking residue.

Properties	Mean[1]	S.D.[2]
pH	8.2	0.2
Total Organic Carbon (%)	26	1.3
Total Carbonate (%)	18.1	0.4
Total Sulfur (%)	0.07	0.00
Sulfate-Sulfur (mg kg^{-1})	24.8	4.6
Total Kjeldahl Nitrogen (%)	0.21	0.03
Nitrate-Nitrogen (mg kg^{-1})	1.4	0.2
Phosphorus, Olsen-P (mg kg^{-1})	13.4	2.1
Chloride (mg kg^{-1})	287.6	22.0
C:N Ratio	123	18
CEC (meq 100 g^{-1})	8	1.2
Conductivity (mmhos cm^{-1})	0.4	0.0
Extractable DTPA Concentrations (mg kg^{-1})		
Copper	1.39	0.22
Zinc	12.07	1.68
Manganese	1.43	0.26
Cadmium	0.22	0.11
Chromium	0.17	0.03
Nickel	0.48	0.07
Lead	1.87	1.00
Total Elemental Concentrations (mg kg^{-1})		
Potassium	47.73	12.47
Calcium	69214.60	5432.69
Magnesium	659.13	31.37
Sodium	132.18	12.27
Aluminum	4451.18	263.31
Iron	185.69	8.85
Manganese	9.49	0.62
Zinc	38.67	11.23
Copper	3.12	0.23
Boron	1.56	0.08
Lead	2.84	0.96
Nickel	1.28	0.67
Chromium	4.89	0.27
Cadmium	0.20	0.11

[1]Mean of five replicates.
[2]S.D. = standard deviation.

Table 4. Concentrations of metals in de-inking residue in comparison to ceiling concentrations for the land application of sewage sludge.

Metal	EPA Ceiling Conc. (mg kg^{-1})	De-inking Residue (mg kg^{-1})
Cadmium	85	0.20
Chromium	3000	4.89
Copper	4300	3.12
Lead	840	2.84
Nickel	420	1.28
Zinc	7500	38.67

The highest boron level, 0.29 mg l^{-1}, was measured in August 1992 on a control plot (Figure 2). The MCL for boron is 0.3 mg l^{-1}. Boron levels were slightly higher in 1992 as compared to 1993 for both the control and residue amended plot at 44.8 Mg ha^{-1}. De-inking residue did not appear to affect the level of boron in sub-surface water at a depth of 122 cm and boron levels did not exceed the drinking water standard during this monitoring period.

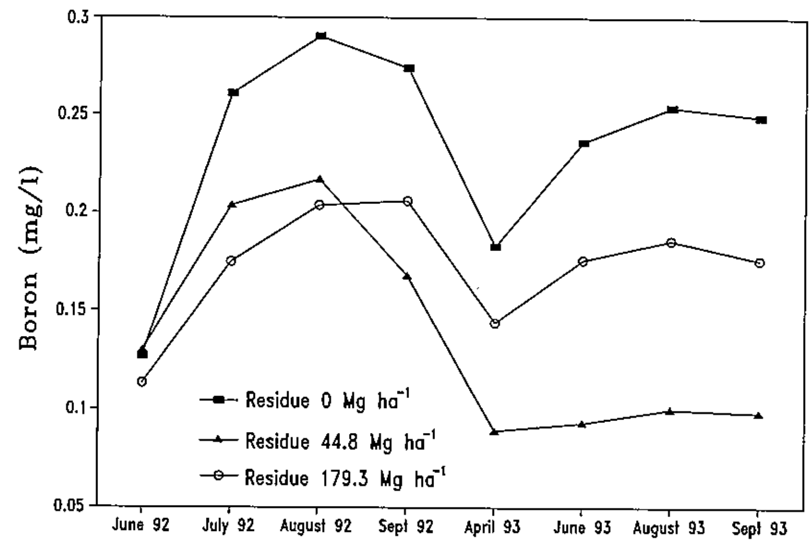


Figure 2. Lysimeter analysis for boron on tailings amended with residue at 0, 44.8, and 179.3 Mg ha^{-1} without fertilizer.

The water analyses for chloride on the plot fertilized with 448 kg ha^{-1} of 18-46-0 (N=81 kg ha^{-1}, P_2O_5=206 kg ha^{-1}) are shown in Figure 3. Chloride concentrations were slightly elevated in 1992 shortly after plot establishment but decreased rapidly during the period June 1992 through September 1993. The results suggest that slightly elevated chloride levels in sub-surface water may be related to chloride in de-inking residue applied at a high rate of application, although chloride did not exceed the drinking water standard of 250 mg l^{-1}.

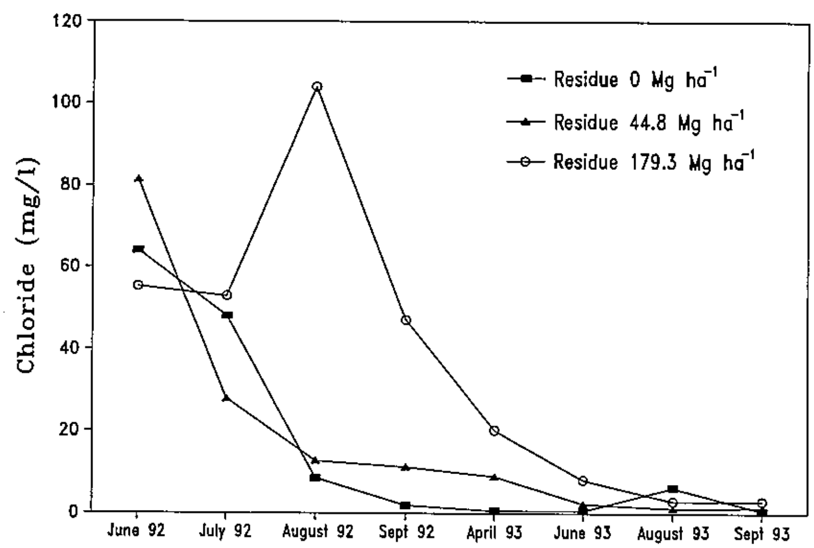


Figure 3. Lysimeter analysis for chloride on tailings amended with residue at 0, 44.8, and 179.3 Mg ha^{-1} and N = 40 kg ha^{-1}, P_2O_5 = 103 kg ha^{-1}.

Vegetative Cover

Weather conditions during the growing seasons at Eveleth Mines in 1992 and 1993 were generally cooler and wetter than normal. The summer of 1992 was particularly cool and these cool conditions likely contributed to low vegetative cover estimates measured in 1992 at Eveleth Mines.

Introduced Species

In July 1992, five weeks after plot establishment, there was a response in the vegetative cover of introduced species to the main effects of de-inking residue and fertilizer (Table 5). Overall, plant cover was significantly higher on tailings without de-inking residue and cover increased somewhat as the level of fertilization increased. At the low fertilizer rate of N=40 kg ha^{-1} and P_2O_5=103 kg ha^{-1}, cover was significantly higher on tailings without residue and with residue at 89.7 Mg ha^{-1}. At the highest fertilizer rate of N=81 kg ha^{-1} and P_2O_5=206 kg ha^{-1}, a significantly higher cover occurred on tailings without residue. There were no significant differences in cover among the residue treatments in July 1992. The effects of fertilization and de-inking residue on plant growth were not pronounced in July 1992 because of the short time interval between plot establishment and the first estimate of vegetative cover.

Table 5. The mean percent vegetative cover of introduced plant species in 1992 and 1993.[1]

Date	Fertilizer Rate (kg ha^{-1})	De-inking Residue Rate (Mg ha^{-1})				
		0	22.4	44.8	89.7	179.3
July 1992	None	11.1a	4.4b	5.6b	7.8 ab	3.3b
	N=40; P_2O_5=103	17.2a	14.4b	4.4b	10.0ab	4.4b
	N=81; P_2O_5=206	18.3a	3.3b	3.3b	7.8b	5.6b
Sept. 1992	None	5.8a	0a	2.2a	1.7a	3.9a
	N=40; P_2O_5=103	21.1a	26.7a	30.0ab	24.4a	6.7ac
	N=90; P_2O_5=202	37.8a	25.6ab	42.2ab	20.0abc	12.2bc
	N=81; P_2O_5=206	33.9a	48.9a	50.0a	30.0ab	10.0b
	N=179; P_2O_5=402	49.4a	48.9a	50.0a	34.4ab	15.6b
July 1993	None	3.9a	0a	1.7a	1.1a	0.6a
	N=40; P_2O_5=103	18.3a	60.0b	53.3b	40.0b	8.9a
	N=90; P_2O_5=202	27.2a	48.9b	55.6b	44.4ab	16.7ac
	N=81; P_2O_5=206	24.4a	65.6b	61.1b	55.6b	21.1a
	N=179; P_2O_5=402	40.6a	67.8b	60.0b	55.6ab	26.7ac
Sept. 1993	None	11.7a	0.6b	1.1b	4.4ab	0.6b
	N=40; P_2O_5=103	32.8a	60.0b	54.4b	46.7ab	24.4ac
	N=90; P_2O_5=202	61.1a	65.6a	75.6ab	53.3ac	22.2d
	N=81; P_2O_5=206	49.4a	75.6b	67.8bc	56.7ac	32.2d
	N=179; P_2O_5=402	77.2a	90.0a	86.7a	75.6a	44.4b

[1]Means within the same row followed by the same letter are not significantly different at the 0.05 level.

Plant cover estimates in September 1992 represent conditions at the end of one growing season. There was a response in the cover of introduced species to the main effects of fertilizer and de-inking residue. The highest cover estimates occurred on tailings fertilized at higher rates, without residue and with residue applied at 22.4 and 44.8 Mg ha^{-1}. At a fertilizer rate of N=81 kg ha^{-1} and P_2O_5=206 kg ha^{-1}, 50 percent plant cover occurred with residue applied at 44.8 Mg ha^{-1}, although this cover was not significantly different than cover on tailings without residue and with residue applied at 22.4 and 89.7 Mg ha^{-1}. At the same fertilizer rate, a low plant cover of 10 percent occurred on tailings amended with residue at 179.3 Mg ha^{-1}. At the highest fertilizer level of N=179 kg ha^{-1} and P_2O_5=402 kg ha^{-1}, 50 percent cover occurred on tailings amended with residue at 44.8 Mg ha^{-1}, although this cover was not significantly different than the cover on tailings without residue and with residue applied at 22.4 and 89.7 Mg ha^{-1}, while a low plant cover of 15.6 percent occurred on residue amended tailings at 179.3 Mg ha^{-1}.

There was a response in the cover of introduced species to the main effects of fertilizer and de-inking residue in July 1993. The cover estimates for introduced species in July 1993 generally indicate that higher cover estimates occurred on fertilized tailings with residue applied at 22.4 and 44.8 Mg ha^{-1}. At the highest fertilizer level, N=179 kg ha^{-1} and P_20_5=402 kg ha^{-1}, there were significant differences in plant cover among residue treatments, ranging from 26.7 percent on tailings amended with residue at 179.3 Mg ha^{-1} to 67.8 percent on tailings amended with residue at 22.4 Mg ha^{-1}. At the highest fertilizer level, a significantly higher plant cover occurred on residue amended tailings at 22.4, 44.8, and 89.7 Mg ha^{-1}, although plant cover at 89.7 Mg ha^{-1} was not significantly different from cover estimates without residue and with residue applied at 179.3 Mg ha^{-1}. Overall, the highest vegetative cover of introduced species occurred with fertilizer and de-inking residue applied at 22.4 and 44.8 Mg ha^{-1}.

In September 1993, cover estimates of introduced species represent plant growth after two full growing seasons. There was a significant response in vegetative cover of introduced species to the main effects of de-inking residue and fertilizer. In general, significant increases in the cover of introduced species occurred as the level of fertilization increased and the highest cover estimates occurred on fertilized tailings with de-inking residue applied at 22.4 and 44.8 Mg ha^{-1}. Without fertilizer, plant cover continued to be very low, less than 12 percent cover after two years. The results clearly show that fertilizer is required for the reclamation of coarse taconite tailings, with or without de-inking residue. At the intermediate fertilizer levels of N=90 kg ha^{-1} and P_2O_5=202 kg ha^{-1}, and at N=81 kg ha^{-1} and P_2O_5=206 kg ha^{-1}, a high plant cover occurred with residue applied at 22.4 and 44.8 Mg ha^{-1}, with plant cover ranging between 65.6 percent and 75.6 percent after two years of growth. The lowest plant covers, 22.2 percent and 32.2 percent, occurred on residue amended tailings at 179.3 Mg ha^{-1} at the intermediate fertilizer levels mentioned above.

Overall, plant cover for introduced species was highest after two years when fertilizer was applied at the highest level of N=179 kg ha^{-1} and P_2O_5=402 kg ha^{-1}. At this high fertilizer level, vegetative cover ranged from 44.4 percent on residue amended tailings at 179.3 Mg ha^{-1} to 90 percent cover with residue applied at 22.4 Mg ha^{-1}. Vegetative cover on tailings at this same high fertilizer level, without residue, and with residue amended at 22.4, 44.8, and 89.7 Mg ha^{-1}, were not significantly different, although plant cover was significantly lower at a residue rate of 179.3 Mg ha^{-1}. A 90 percent plant cover was achieved by the introduced species at the end of the second season using this high fertilizer level with de-inking residue applied at 22.4 Mg ha^{-1}.

Native Species

Very low vegetative cover estimates occurred on tailings planted to native species in July 1992 (Table 6). After a growth period of five weeks, there were no significant differences in plant cover on tailings without fertilizer and with fertilizer applied at N=40 kg ha^{-1} and P_2O_5=103 kg ha^{-1}. At a fertilizer rate of N=81 kg ha^{-1} and P_2O_5=206 kg ha^{-1}, there were significant differences in cover estimates among residue rates, but cover estimates on all treatments were less than 5 percent. Initial cover estimates indicate that de-inking residue did not benefit the establishment of native plant species on coarse taconite tailings.

Table 6. The mean percent vegetative cover of native plant species in 1992 and 1993.[1]

Date	Fertilizer Rate ($kg\ ha^{-1}$)	De-inking Residue Rate ($Mg\ ha^{-1}$)				
		0	22.4	44.8	89.7	179.3
July 1992	None	1.7a	0a	1.1a	1.1a	2.2a
	N=40; P_2O_5=103	1.7a	0a	0a	0a	1.1a
	N=81; P_2O_5=206	1.1a	3.3b	2.2ab	1.1ab	4.4bc
Sept. 1992	None	3.6a	1.7a	1.1a	0.6a	1.1a
	N=40; P_2O_5=103	10.0a	1.1b	2.2ab	0b	0b
	N=90; P_2O_5=202	5.6a	1.1a	1.1a	1.1a	1.1a
	N=81; P_2O_5=206	14.4a	1.1b	3.3b	2.2b	0b
	N=179; P_2O_5=402	11.7a	6.7ab	1.1b	1.1b	0b
July 1993	None	3.3a	0a	0.6a	1.1a	0.6a
	N=40; P_2O_5=103	11.7a	1.1ac	0bc	0bc	0bc
	N=90; P_2O_5=202	13.3a	14.4a	1.1b	0b	2.2b
	N=81; P_2O_5=206	16.1a	4.4b	3.3b	0b	1.1b
	N=179; P_2O_5=402	22.8a	27.8ab	14.4ac	1.1d	1.1d
Sept. 1993	None	12.2a	7.8ab	5.0ab	2.2b	2.2b
	N=40; P_2O_5=103	29.4a	6.7b	5.6b	0b	1.1b
	N=90; P_2O_5=202	37.2a	36.7a	12.2b	4.4b	2.2b
	N=81; P_2O_5=206	36.1a	20.0b	18.9b	5.6b	2.2d
	N=179; P_2O_5=402	54.4a	68.9a	41.1ab	32.2bc	2.2d

[1]Means within the same row followed by the same letter are not significantly different at the 0.05 level.

There was a response in cover of native species to the main effect of de-inking residue but not to fertilizer in September 1992. After one growing season, the highest plant cover of native species occurred on tailings that were only fertilized with no residue. On fertilized tailings without de-inking residue, vegetative cover ranged from 5.6 percent to 14.4 percent. With de-inking residue and fertilizer, plant cover was generally less than 3 percent. These results indicate that de-inking residue negatively impacted the growth of native species during the first year.

In July 1993, there was a response in cover of native species to the main effects of fertilizer and de-inking residue. Without any fertilizer and with fertilizer applied at the lowest rate, N=40 $kg\ ha^{-1}$ and P_2O_5=103 $kg\ ha^{-1}$, plant cover was typically less than 4 percent. At the lowest fertilizer rate, plant cover was essentially bare on residue amended tailings. The highest vegetative cover occurred at the highest fertilizer level of N=179 $kg\ ha^{-1}$ and P_2O_5=402 $kg\ ha^{-1}$. At this high fertilizer level, a significantly higher cover occurred on tailings without residue and with residue applied at 22.4 and 44.8 $Mg\ ha^{-1}$, with cover ranging between 14.4 percent and 27.8 percent. At this high fertilizer level, a significantly lower vegetative cover of 1.1 percent occurred when residue was applied at 89.7 and 179.3 $Mg\ ha^{-1}$. The native species continued to have lower plant cover estimates as compared to introduced species in July 1993.

There was a significant response in plant cover of native species to the main effects of fertilizer and de-inking residue in September 1993. Without any fertilizer and with fertilizer applied at the lowest level, N=40 kg ha^{-1} and P_2O_5=103kg ha^{-1}, plant cover was low on all residue amended tailings. At the low fertilizer level of N=40 kg ha^{-1} and P_2O_5=103 kg ha^{-1}, a significantly higher cover occurred on tailings with only fertilizer as compared to residue treatments. Higher cover estimates were measured at intermediate and high fertilizer rates. At intermediate fertilizer rates, N=90 kg ha^{-1} and P_2O_5=202 kg ha^{-1} and at N=81 kg ha^{-1} and P_2O_5=206 kg ha^{-1}, plant cover was highest when no de-inking residue was applied and when residue was applied at 22.4 Mg ha^{-1}. A significantly lower cover occurred, at the intermediate fertilizer rates mentioned above, when residue was applied at 44.8, 89.7, and 179.3 Mg ha^{-1}, where plant cover was less than 20 percent. At the highest fertilizer rate, N=179 kg ha^{-1} and P_2O_5=402 kg ha^{-1}, plant cover ranged from 2.2 percent with residue applied at 179.3 Mg ha^{-1} to 68.9 percent on residue amended tailings at 22.4 Mg ha^{-1}. Vegetative cover on tailings without residue and with residue applied at 22.4 and 44.8 Mg ha^{-1} were not significantly different.

Canada wild rye and kalm's brome appeared to be the most abundant of the native species, although little bluestem and big bluestem were present. The above-ground biomass of many native species appeared minimal at the end of the second growing season, particularly little bluestem and big bluestem, and bush clover. Although the introduced species had higher vegetative cover estimates than native species in September 1993, the differences between the two plant groups were less pronounced in September 1993 as compared to plant cover estimates in 1992.

Conclusions

The inherently poor physical, chemical, and biological characteristics of coarse tailings were not ameliorated with the application of de-inking residue at Eveleth Mines. Coarse tailings, both before and after the application of de-inking residue, had a high pH, low organic matter and nutrient contents, and a low cation exchange capacity.

De-inking residue has a high C:N ratio, indicating that immobilization of nitrogen would occur if residue is land applied without adequate levels of supplemental nitrogen. De-inking residue is not a significant source of other plant nutrients. Metal concentrations in de-inking residue were less than 1 percent of the ceiling concentrations allowed in municipal sewage sludge to be land applied.

De-inking residue did not effect the level of boron and chloride in sub-surface water. Although chloride was higher in 1992 shortly after plot establishment as compared to 1993, chloride in sub-surface water did not exceed the drinking water standard at the highest de-inking residue rate.

The effect of fertilization on plant growth was minimal in the initial stages of plant establishment. De-inking residue negatively impacted plant growth during the period of establishment, although cool, wet conditions during this time may account for some initial slow growth rates. At the end of the first growing season, vegetative cover estimates for introduced species indicate that the highest cover estimates occurred on tailings fertilized at the highest rate without residue and with residue amended at 22.4 and 44.8 Mg ha^{-1}. At the end of the first growing season, native plant species generally had the highest cover on fertilized tailings without de-inking residue. Low cover estimates of native species in the first two years is expected since much of its growth is in the development of its root system.

During the peak of the second growing season in July 1993, introduced species had higher cover estimates on tailings fertilized at the highest rates with residue applied at 22.4 and 44.8 Mg ha^{-1}. Native species had higher cover estimates on tailings fertilized at the highest level, without residue, and to a lesser degree with residue applied at 22.4 Mg ha^{-1}. At the end of the second growing season in September 1993, introduced species had a 90 percent cover on tailings with fertilizer applied at the highest rate and with residue applied at 22.4 Mg ha^{-1}. The highest cover for introduced species generally occurred on fertilized tailings without residue and with residue applied at 22.4, 44.8, and 89.7 Mg ha^{-1}. At the end of the second growing season, native species had the highest cover on tailings fertilized at the highest rate without residue and with residue applied at 22.4 and 44.8 Mg ha^{-1}. Although neither vegetative cover or biomass of specific species were measured, alfalfa and smooth bromegrass appeared to be the most abundant introduced species, while Canada wild rye and kalm's brome appeared to be the most abundant native species.

Vegetative cover for introduced species increased from no cover, prior to plot establishment, to 49 percent at the end of the first growing season, to 90 percent at the end of the second growing season on tailings fertilized at the highest level with 22.4 Mg ha^{-1} of de-inking residue. At this same fertilizer and residue rate, vegetative cover for native plants increased from no cover before plot establishment, to 7 percent at the end of the first growing season, to 69 percent at the end of the second growing season. Based upon this two-year study, the highest vegetative cover using introduced species was achieved after two growing seasons using de-inking residue applied at 22.4 Mg ha^{-1} with fertilizer at a high rate of application.

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