

Appendix J: Mine Tailing Revegetation (Lakehead University)

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Mine Tailing Revegetation

A report prepared for Marathon PGM

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1. Non-technical summary

In the summer of 2009 tailings were obtained from Marathon-PGM for greenhouse revegetation trials at Lakehead University in Thunder Bay, Ontario. Revegetation trials were conducted in 2 L pots containing tailings and amendments. Amendments selected were fertilizer, wood chips, wood mulch, wood ash, charcoal, and natural forest soil. The amendments were selected based on their relative abundance and potential to act as a source of nutrients.

Species chosen for revegetation were part of a Ministry of Transportation of Ontario road mixture (red clover, Kentucky bluegrass, perennial rye grass, and red fescue). This mix was chosen because it is inexpensive, widely available, has a long history of use in revegetation work, and contains a nitrogen fixing species and perennial grass species.

Amendments were used in three different amounts. Pots were sown with 200 seeds each. After 150 days the experiment was ended. Water was collected from each pot and analyzed for soil nutrients and the biomass of vegetation in each pot was determined.

Fertilizer and natural forest soil amendments improved plant growth significantly over unamended tailings. The two amendments performed relatively equally. The other amendments were not found to increase plant biomass. Soil nutrients were increased somewhat by forest soil additions, but were negatively affected by wood chip and wood mulch additions. Wood ash additions increased some soil nutrients but also increased some undesired soil elements.

Based on the results of this study it is recommended that natural forest soil be used as a tailing amendment as it is expected to have longer lasting effects than fertilizer and is locally abundant and can be managed onsite.

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2. Introduction

Revegetation of large disturbed areas often requires assistance to ensure successful establishment and adequate growth of species in order to return these areas to an acceptable state. Mine tailings can be particularly problematic, and often remain poorly vegetated for many years, centuries in extreme cases (Ash et al. 1994). The absence of a proper nutrient cycle, as well as toxic conditions in some tailings inhibit natural revegetation of mine tailings (Lan et al. 1998; Shu et al. 2005), making active revegetation methods necessary in order to ensure tailings are revegetated to a point where they are stable and natural processes can proceed without ongoing intervention.

The proposed Marathon PGM-Cu mine will create a large tailings pond that is unlikely to revegetate naturally within a reasonable period (e.g. 50 years). It is therefore expected that some form of active revegetation will be required. The purpose to this study is to identify the potential low-cost methods to improve revegetation success, with emphasis on the following objectives:

- The growth of plants on various amendments
- Effects of amendments on soil nutrients and potentially toxic elements

1.1 Summary of tailings assessment

A preliminary examination of tailings obtained in July of 2008 was conducted (See Luckai & Hart 2009). Laboratory analysis found tailing pH to be between 7.5-8.0, and thus posing no risk of acid mine drainage and mobilization of toxic elements (Brady & Weil 2004). Extractable levels of copper, zinc, and iron were extremely low and most non-essential elements in solution were negligible. However, macronutrient (nutrients required by plants in large amounts) levels

were found to be very low, with deficient levels of nitrogen and phosphorus. The tailings were also found to be very coarse textured, possibly resulting in poor water retention, while the low clay content may lead to low cation exchange capacity and poor nutrient retention.

Based on the tailing assessment it was concluded that organic matter additions would be required to increase the likelihood of vegetation establishment and continued growth, eventually leading to a sustainable vegetation community and nutrient cycling. Because of the large proposed tailings area (25 km²) and relative remoteness of the mine site, it was recommended that tailing amendments focus on relatively cheap and abundant nutrient sources including wood chips, wood ash, local forest soil, and fertilizer. A seed mixture containing perennial species and nitrogen fixing species was also recommended.

2 Methods

2.1 Greenhouse trials

Greenhouse trials are limited in scope because of their inability to properly mimic environmental conditions present on mine tailings. Greenhouse trials focused on the effects of various tailing amendments (wood ash, fly ash, wood chips, mulch, and fertilizer) on tailing properties and plant growth (Maboeta & Van Rensburg 2003; Bradshaw & Chadwick 1980; Ye et al. 2000). The purpose of the trials was to evaluate the effectiveness of a number of amendments to increase soil nutrient properties and plant growth (Jefferies et al. 1981b; Jefferies et al. 1981a).

Greenhouse trials were conducted using 2 L containers (approx. 13 cm diameter x 15 cm depth), to evaluate the effects of amendments on plant performance and physical and chemical properties of the tailings (Maddocks et al. 2004; Yang et al. 1997; Maboeta & Van Rensburg

2003). Containers were lined with a 0.1 mm plastic screen and filter paper to prevent loss of tailings (Ye *et al.* 2001), and filled to the 2 L mark (Photo 2.1).



Photograph 2.1. A container filled with unamended tailings, prior to seeding.

Treatments were replicated four times using a completely randomized design (Photo 2.2) and carried out for 15 weeks (Piha *et al.* 1995). A Ministry of Transportation of Ontario seed mix (MTO seed mix) was used for the trials. The mix contains four species, three grasses and one legume (Table 3.1). The MTO seed mix is used extensively in roadside revegetation is relatively inexpensive and widely available.



Photograph 2.2. Vegetation trial setup in the greenhouse at Lakehead University (left), showing completely randomized design (right).

Table 2.1. Species composition of MTO seed mix.

Common Name	Scientific Name	Functional Group	Notes
Red fescue	<i>Festuca rubra</i>	Perennial grass	Native to parts of Canada, naturalized in all of southern Canada
Kentucky blue grass	<i>Poa pratensis</i>	Perennial grass	Native to Canada, naturalized elsewhere
Perennial ryegrass	<i>Lolium perenne</i>	Perennial grass	Naturalized throughout Ontario
Red clover	<i>Trifolium pratense</i>	Short lived perennial; legume	Naturalized throughout Ontario

Tailing amendments are listed in table 2.2 (below). Amendments were selected based on local availability, low cost, and potential benefits. All amendments were air dried for 96hrs at room temperature. In the case of the native soil, the soil was not sterilized and any seeds germinating from the seed bank were included in the study. Each container was seeded with 200 seeds, buried to a depth of 1.0 cm. Pots were watered with 250 mL twice a week.

Table 2.2. Tailing amendments.

Amendment	Benefits	Quantities (t/ha)	Notes
Control	None	-	Unamended tailings
Fertilizer	Fast input of nutrients	0.1, 0.2, 0.4	Standard NPK (10:10:10)
Boiler ash (charcoal)	Nutrient retention	5,10,20	Similar to charcoal, contains some ash and nutrients
Fly ash	High nutrient content	1, 5, 10	May pose heavy metal issues
Mulch	Organic matter and some nutrient content	40, 80, 120	Partially decomposed wood waste; very abundant
Wood chips	Organic matter and some nutrient content	40, 80, 120	Fresh wood waste; very abundant
Native soil	Presence of microorganisms, nutrient cycle, and potentially dormant propagules	40, 80, 120	Locally abundant and likely to contain native seed bank.

After 15 weeks soil leachate was collected by percolating 500 mL of distilled water through each container, the leachate was collected in 100 mL bottles. Leachate was filtered and submitted for inductively coupled plasma (ICP) analysis for metals and nutrients, as well as ammonium and nitrate analysis. For plant productivity analysis, plants were removed from the pots at the end of the experiment, the roots were washed to remove tailings, and roots and shoots air dried at 105 °C for 12 hrs to determine dry weight.

2.2 Data analyses

We were interested in studying the effects of both treatment type and the amount of specific treatment on the levels of chemical elements and pH in the tailings. The amount of treatment was viewed as a factor nested under treatment type (Table 3.2). A nested analysis of variance (ANOVA) model was used, including seven treatments and treatment amounts nested within a

treatment type as factors. Dependent variables were plant biomass, amounts of macronutrients (nitrogen (N), phosphorus (P), potassium (K), and sulphur (S)), micronutrients (boron (B), calcium (Ca), cobalt (Co), copper (Cu), magnesium (Mg), manganese (Mn), molybdenum (Mo), sodium (Na), nickel (Ni), and zinc (Zn)), other soil elements (aluminum (Al), barium (Ba), chromium (Cr), strontium (Sr) and lithium (Li)), pH, and plant dry weight. To achieve homogeneity of variance and normality, the levels of P, Co, Cu, Zn, Ni and pH were \log_{10} transformed. Differences between treatments were studied using Hochberg's post-hoc test. To test differences among treatment amounts, a one-way ANOVA was run separately for each treatment type with treatment amount as predictor variable. Results were interpreted using the control treatment group as a reference. The analyses were made using the statistical analysis program SPSS Statistics 17.0 (SPSS Inc. 2008).

3 Results

3.1 Plant growth

Establishment and growth of red clover was very poor. In many pots no growth was observed. Although anecdotal, establishment appeared to be limited to pots amended with native soil, wood chips, or mulch. In all cases, however, red clover was a very small proportion of overall plant cover. No fruiting bodies were observed on grasses, making identification of species difficult. As a result, no attempt was made to account for species and a cumulative dry weight was used for plant biomass. As well, no germination of dormant seeds was observed for native soil amendments, and as a result no additional species needed to be included in the trial.

Plant dry weight (Fig. 3.1) was somewhat affected by treatment. Fertilizer (Fert.) and Native Soil (NS) treatments had somewhat significantly greater plant biomass ($p = 0.083$). There

was, however, a significant effect in the amount of fertilizer ($p < 0.001$), native soil ($p = 0.009$), and wood chips ($p = 0.031$) dosage. For wood chips, however, dry weight was not significantly different from the control treatment. Fertilizer and native soil additions of 0.2 and 40 t/ha, respectively showed marked increases in plant biomass, whereas fertilizer inputs of 0.1 t/ha were not significantly different from the control treatment. Large amendments of fertilizer and native soil had a relatively equal impact on plant biomass with large increases in dry weight at 0.4 and 120 t/ha, respectively.

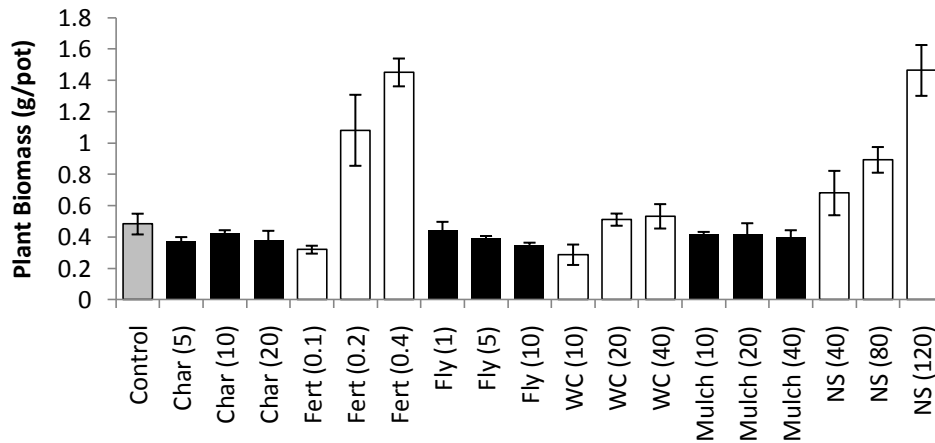


Figure 3.1 Plant biomass (dry weight) by treatment and dosage (t/ha).

3.2 Macronutrients

Nitrate and ammonia concentration readings were erroneous and have not been included in the study. Charcoal addition increased soil phosphorus (P), but had no influence on the content of other macronutrients. Fly ash treatment had a positive influence on soil potassium (K), with K

increasing with increasing dosage of fly ash addition. Fertiliser, wood chips (WC) and mulch treatments decreased extractable sulphur (S).

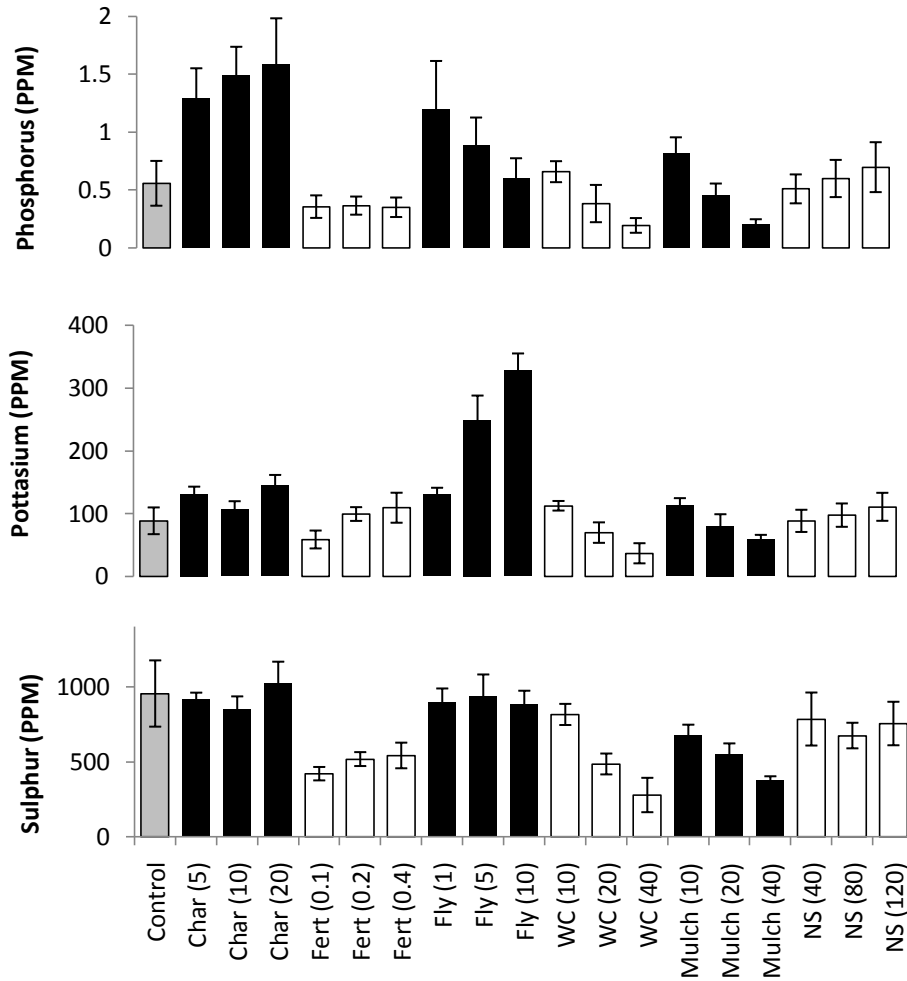


Figure 3.2. Macronutrients in leachate by treatment type and dosage (t/ha).

3.3 Micronutrients

Fly ash additions increase increased soil boron (B). In addition, there was a positive relationship between increasing amounts of fly ash and B content. The increasing amounts of wood chips decreased soil B content. Fertiliser treatment decreased soil cobalt (Co), magnesium (Mg), and manganese (Mn). Magnesium and Mn were also negatively affected by mulch and native soil

treatments. Zinc (Zn) content was highest following charcoal addition and lowest following fertiliser and Mulch treatments; however, compared to the control untreated soils, the difference was not significant. Soil cooper (Cu) and molybdenum (Mo) were not influenced by any amendment type.

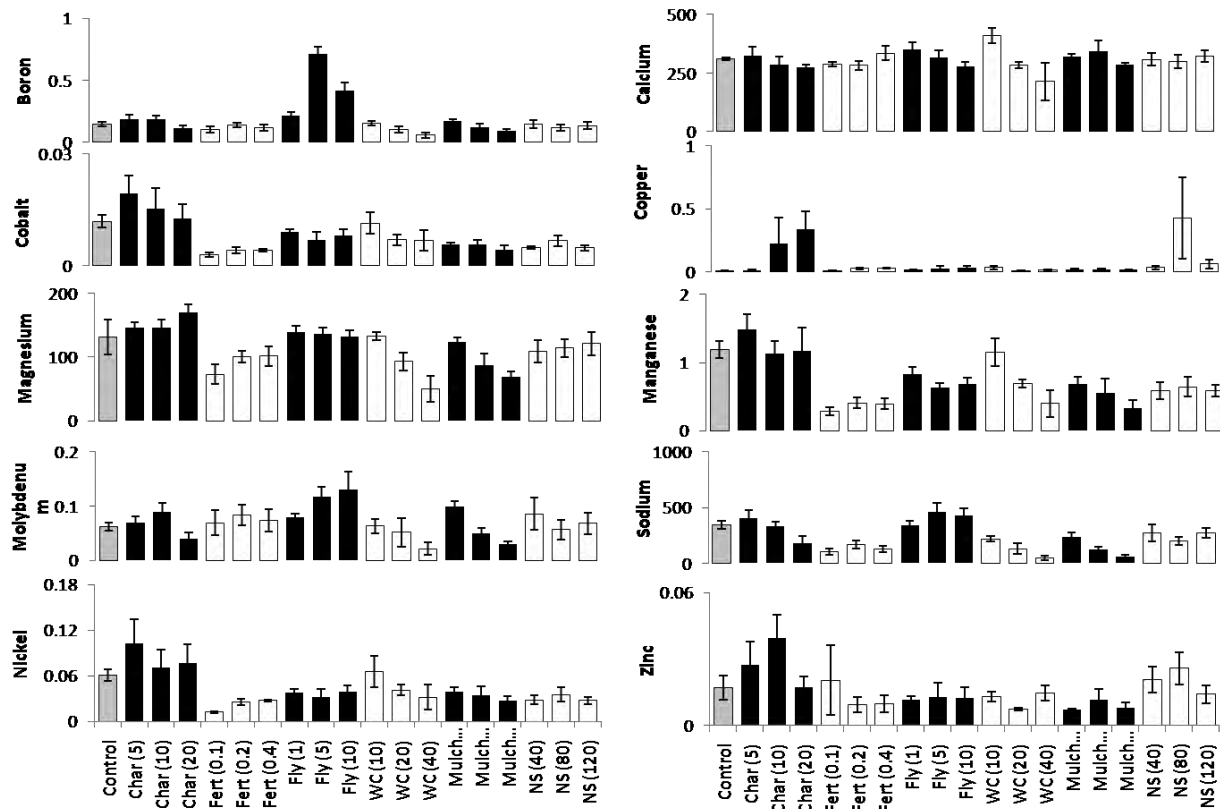


Figure 3.3. Micronutrients in leachate (PPM) for each treatment type and dosage (t/ha).

3.4 Other elements

Mulch treatment significantly increased soil aluminum (Al) content. The increase was also higher with increasing mulch treatment. Charcoal increased soil sodium (Na) and somewhat increased chromium (Cr) content. The amounts of sodium (Na) in the soil were positively

affected by fly ash addition. Nickel (Ni) was lowest after fertiliser addition. Strontium (Sr) content was higher after charcoal and fly ash treatment compared to fertiliser and wood chip treatment; however, the difference from untreated soils was not significant. Treatment type did not have any effect on barium (Ba) and Lithium (Li). Increasing amounts of wood chip and mulch treatments decreased the content of Ba, Ni, Na, Sr and Li.

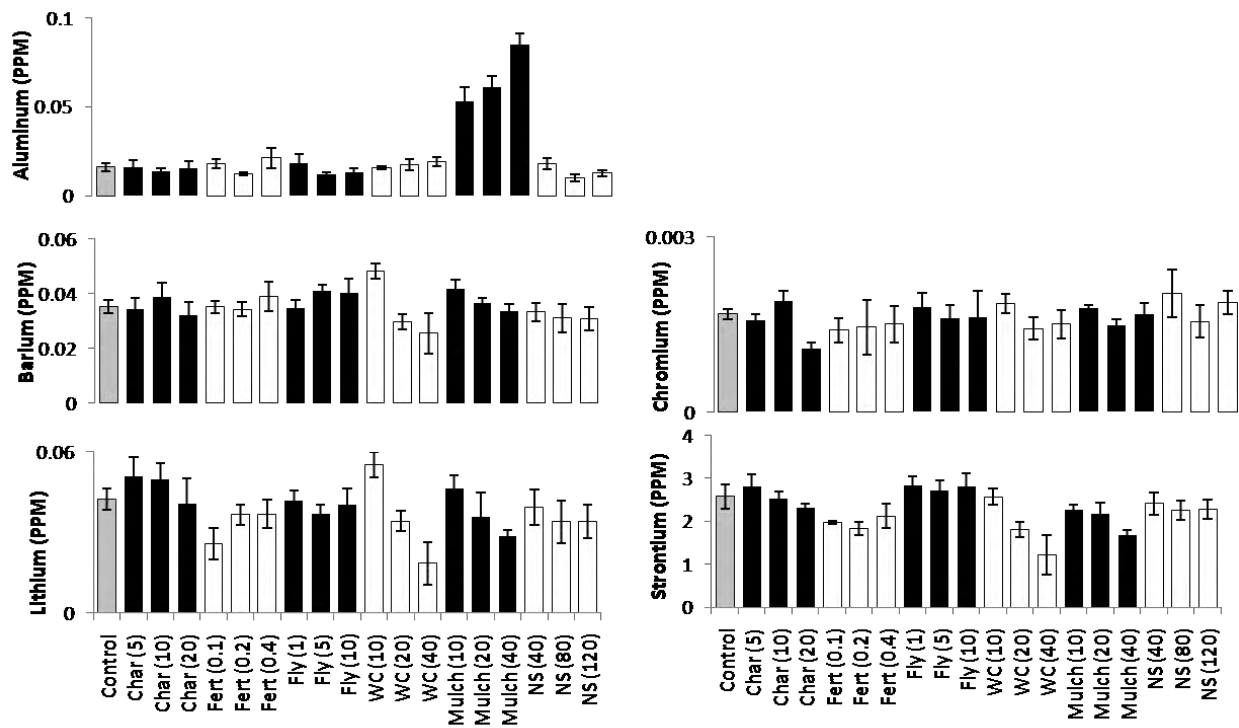


Figure 3.4. Elements in leachate (PPM) for each treatment type and dosage (t/ha).

3.5 pH

Acidity of treated soils did not differ compared to control (untreated) soils. However, fertiliser treatment and mulch treatment resulted in somewhat higher pH levels compared to native soil treatments (Fig. 3.5).

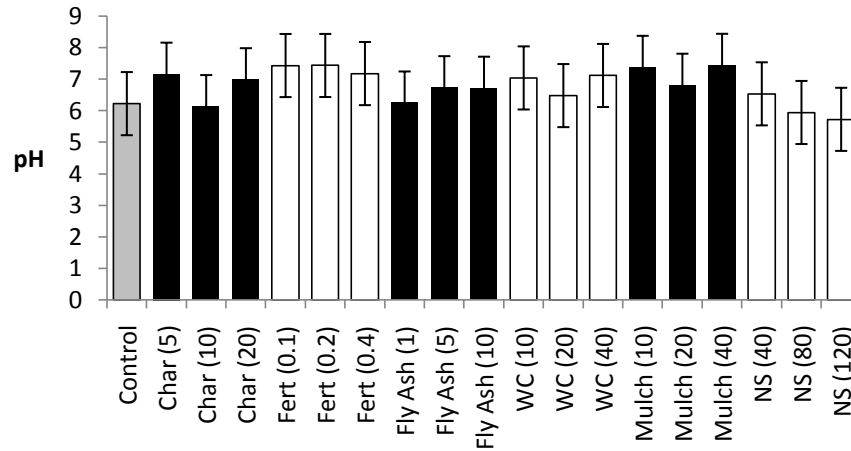


Figure 3.5. pH of leachate for each amendment and dosage (t/ha). Error bars are +/- 1 SE.

4 Discussion

4.1 Plant growth

Poor growth and establishment of red clover may be the result of phosphorus (P) deficiency in the tailings (Dancer et al. 1977). Previous analyses of unamended tailings found available P was very low, and considered to be deficient. As well, a lack of rhizobial inoculum in the otherwise sterile soils may explain the poor establishment of any red clover in most pots. Pots that did have some clover germination and growth were those amended with wood chips, native soil, and mulch. These amendments were not sterile and likely contained an array of microbial communities, some of which may have been suitable inoculum. Even in these pots, however, growth of red clover was very poor, likely reflecting P deficiency. Treatments that were found to increase P, such as charcoal (Fig. 3.2), were sterile and thus not able to provide any rhizobium.

The absence of dormant seeds or propagules in the native soil amendments may be the result of soil selected for the treatment. Soil was taken from below the organic LFH (litter) layers

to avoid adding large amounts of organic matter as part of the treatment. Buried seeds and propagules are often found in the LFH and A (topsoil) horizons (Moore & Wein 1977). Because forest LFH layers are relatively thin it is likely that attempts to amend with native forest soil would result in primarily inorganic horizons being added.

Only fertilizer and native soil treatments showed increases in plant biomass. For both of these amendments the increase in plant biomass was significant, with both showing twice the yield as the control treatment. Of particular interest is that the two treatments resulted in nearly identical yields at the highest respective dosages, suggesting that both amendments can have a similar effect on plant biomass. The highly labile nature of fertilizer, however, suggests that the benefit of fertilizer may be short lived, whereas the complex array of soil particles and organic matter in native soil suggests that a number of factors may be contributing to the increased plant biomass, including increased macro and micronutrient availability, microbial populations, and symbiotic fungi, as well as soil properties such as cation exchange capacity (CEC), and water retention. As a result, the effects of native soil treatments may last much longer.

4.2 Treatments

4.2.1 Charcoal

Although a number of studies have found charcoal additions to soil to have a stimulating effect on plant growth and nutrient availability (Lehmann et al. 2006), none was observed in this study. Charcoal also contains an ash component which likely explains the higher levels of phosphorus (P) and potassium (K) found in the leachate (Fig. 3.2), since they are common in all organic matter. Micronutrients and other elements, however, did not appear to be affected by charcoal additions.

Although no short term benefit is apparent from charcoal amendments, there may be a long term benefit from increased nutrient retention and soil conditioning (Downie et al. 2009; Busscher et al. 2009), but longer term studies would be required to investigate these properties. Charcoal may, however, be a good source of P and K. These elements are part of the ash fraction and are not likely to be as mobile as those found in fertilizer, potentially having a more long-term impact over macronutrient availability.

4.2.2 Fertilizer

Relative to the control treatment, fertilizer had very little effect on macro-or micronutrients, as well as any other elements. Given that commercial fertilizers contain only NPK it is not surprising that most other elements would not be affected very much by fertilizer additions. Of interest, however, are the relatively low levels of P and K compared to other treatments. Given that fertilizer contains large amounts of P and K, the low amounts found in the leachate suggest that the forms found in the fertilizer are highly mobile and may have been leached through the normal watering regime. It is likely that additional P and K was taken up by plant growth, stimulated by high N levels (not recorded), but the poor growth of plants in the lowest fertilizer dosage, where levels of P and K were below those of the control, suggest that some leaching has occurred. While the fertilizer treatment had a very pronounced growth response, it may be short lived given the low residence time of the fertilizer (Bradshaw 1992).

Low plant biomass in the 0.1 t/ha fertilizer treatment (Fig. 3.1) suggests that the tailings have significant nutrient limitations that can only be overcome by relatively large nutrient inputs. As a result, amendments must be of sufficient capacity to overcome these nutrient limitations, otherwise poor establishment and growth may result, despite some inputs.

Lower levels of other nutrients (magnesium, manganese, sodium, nickel and sulphur) are likely the result of increased uptake by the rapidly growing vegetation. These nutrients showed little change with increasing dosage but were significantly lower than those found in the control treatment. Rapid uptake of nutrients, stimulated by fertilizer addition may inhibit future nutrient cycling, as most nutrients may become bound inside plant tissue, potentially slowing future vegetation establishment without continued fertilization (Bradshaw 1992).

4.2.3 Fly ash

Although fly ash had no effect on plant biomass, there was a significant effect on soil nutrients. Levels of phosphorus (P) and potassium (K) were much higher than the control. Levels of K increased with increasing dosage, suggesting that fly ash is a good source of K. Interestingly, P levels declined with increasing dosage, although the effect was not significant because of large variation in measured concentrations. Of some concern are the high levels of boron (B) found in fly ash treatments. Although a micronutrient, B is phytotoxic at relatively low levels. As a result, fly ash may not be a good source of nutrients because of possible contamination issues.

4.2.4 Wood chips and Mulch

Both types of wood waste amendments had nearly identical effects on soil nutrients. For macronutrients and some micronutrients there was a decline in concentration with increasing dosage. Given that plant biomass was not affected by the treatments, this is likely the result of adsorption of nutrients on the surface of the wood waste. Organic matter has a high adsorptive capacity and can result in a reduced mobility of nutrients. It is also possible that the high carbon

to nutrient ratios of woody material resulted in microbes robbing the soil of these nutrients when decomposing the woody materials, however this effect would not be expected to be particularly strong. As a result, it appears that wood waste additions may decrease nutrient availability in the short term. In the long term, however, the wood waste would be expected to act as a slow release source of nutrients, but for revegetation treatments wood waste would likely have to be accompanied by an additional source of nutrients, such as fertilizer or more labile organic matter.

Of interest is also the effect of the mulch amendment on aluminum (Al) concentrations (Fig. 3.4), which increased with increasing mulch dosage. Aluminum is highly sensitive to increases in acidity and can reach toxic levels in soils with very low pH (Piha et al. 1995; Brady & Weil 2004). Although not shown by the pH readings, it is possible that a small amount of acidification occurred as a result of mulch treatments. Mulch is often somewhat acidic and would be expected to decrease pH, potentially increasing Al mobility. Soluble ligands (weak organic acids) can also increase the solubility of some metals (Burkhard et al. 1995), and are likely to be present in wood mulch. Treatments that decrease pH should be monitored to ensure that Al toxicity does not occur.

4.2.5 Native soil

Amendment with native forest soil appears to be as, if not more, effective as fertilizer in promoting plant growth. Despite the apparent fertility of the treatment, there was little increase in nutrient concentrations relative to the unamended tailings. To some extent this may be the result of increased nutrient uptake from N found in the soil (not measured), however it is more likely that nutrients are bound to humic substances and in a complex array of labile and stable

forms of organic matter as well as bound to clay particles, thus making nutrients less easily leached from the soil. As well, it is likely that the presence of microorganisms in the forest soil impart better function to the soil in terms of mineralization, nutrient retention, and symbiotic associations. The addition of relatively small (80 -120 t/ha) amounts of forest soil can impart many of the properties of a fully developed soil to mine tailings. The addition of forest soils to mine tailings is likely to be the most sustainable of all tested amendments, by improving the overall function of the soil, rather than just the availability of a few macronutrients.

Although amendment levels are quite large (80 – 120 t/ha), the proximity of large amounts of forest soil onsite makes this type of treatment feasible and very straightforward. Amendment with forest soils will also have the added benefit of improving the soil structure of the tailings, possibly reducing the risk of erosion, compaction, desiccation, and water logging.

4.3 Implications for mine tailing revegetation

Given the expense of fertilizer application and the presence of forest soil onsite, as well as overburden that is removed from surface mining operations, the use of onsite forest soil is likely to be an effective amendment to newly deposited tailings, especially when applied in amounts equivalent to 120 t/ha. Additions of forest soil may also have the added benefit of providing dormant seeds and propagules, potentially increasing species diversity and speeding up succession. Although not evenly distributed throughout the soil column, dormant seeds can be as high as 7000 seeds/m² in the top 2 cm of some soils (Zhang et al. 2001). If fertilizer is used, it is recommended that it be applied at a rate of at least 0.2 t/ha in order to overcome the nutrient deficiency of the tailings.

Use of forest soils should focus on the topsoil layer. This layer contains the organic horizons where the vast majority of nutrients are contained as well as virtually all of the organic matter, soil microbes, and dormant seeds and propagules (Moore & Wein 1977; Zhang et al. 2001; Brady & Weil 2004). Storage of topsoil can be done for up to five years, after which time soils will lose the majority of their organic matter, nutrients, microbial communities, and dormant seeds (Ghose 2001).

The lack of growth response to the other treatments may be the result of the relative stability of these amendment types. Charcoal, wood chips and mulch all decompose very slowly and may not act as short term nutrient sources. Although a number of studies have identified wood waste as an appropriate amendment it appears to require the addition of a source of easily released nutrients, such as fertilizer, manure, or compost, in order to ensure that nutrient availability is not reduced in what are already very nutrient poor soil (Maboeta & Van Rensburg 2003).

4.4 pH

pH was not found to change markedly with treatment. Of interest is that regardless of treatment pH remained in the range of 6-7. This is an ideal pH for most species and comparable to local forest soils. The tailings appear to have adequate buffering capacity, given that treatment type and dosage had no discernable effect.

5 Summary and Recommendations

Conclusive evidence of the success of revegetation efforts can only be gained through long term outdoor trials. Several years of large scale on-site revegetation is likely required to accurately assess the revegetation potential, including successful reproduction, succession, and nutrient status. From the greenhouse trials, however, the following recommendations can be made:

- Addition of wood waste biomass can decrease nutrient availability. This is likely due to adsorption of nutrients onto woody biomass. A small increase in microbial uptake may also be occurring, as the woody biomass has very high carbon to nutrient ratios, and decomposition may rob the soil of nutrients. Additions of woody biomass are not recommended unless accompanied by fertilizer, natural soil, or high nutrient organic matter (ex. manure).
- Local forest soil additions are as effective as fertilizer in promoting plant growth. Natural soil can be obtained on site from the removal of overburden, and impacted surrounding areas. It is recommended that overburden be saved and applied to the tailing surface at rates equivalent to 80 to 120 t/ha to tailings areas ready for revegetation. Rates of application and methods of amendment should be studied in order to determine the most effective ways to carry out this practice, but the overall focus should be on storage and maintenance of topsoil and organic matter.

- Mill waste wood ash can increase levels of some metals known to be phytotoxic and of environmental concern, and does not appear to be effective in promoting plant growth. While a source of some macronutrients, charcoal is also ineffective at promoting plant growth. As a result, the use of these materials is not recommended in the short term. However, it is recommended that further investigation of the interaction of chars with fertilizer and native soil be investigated in longer-term experiments.

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7 Glossary of terms

ANOVA	ANalysis Of VAriance. An overall analysis testing whether group means (averages of different treatments) differ from one another.
CEC	Cation Exchange Capacity. The total amount of exchangeable cations (ex. Ca^{2+} , Mg^{2+} , K^+), elements with a positive charge, that a soil can adsorb at a given pH. Exchangeable cations are held on the surfaces of clay and organic matter particles, which have negative charges.
Completely randomized design	A type of experimental design in which treatments (amendments) are assigned at random to a sample (pot). It is used to study the effects of one primary treatment (amount of one amendment) on a given sample (pot).
Glofor Hochberg's post hoc test	A type of comparison test for comparing the means of all combinations of pairs of treatments. This analysis allows one to determine which means (treatment group averages) differ from one another. This particular test is very robust, and is able to deal with some variation in normality.
ha	Hectare. 10 000 m ² .
ICP Analysis	Inductively Coupled Plasma analysis. A highly sensitive form of mass spectrometry, capable of detecting metals and some non-metals at very low concentrations (below one part in 10 ¹²)
Macronutrients	Inorganic elements required in relatively large amounts (nitrogen, potassium, phosphorus, sulphur)
Micronutrients	Inorganic elements required in very small amounts (ex. Nickel, copper, selenium, sodium)
MTO	Ministry of Transportation of Ontario
Nested ANOVA	A nested ANOVA is used when a nested experiment is conducted. In this case the levels of studied factors (amendment types) have dosages nested within them. Because of this, dosages cannot be compared between treatments and a nested ANOVA is required.

pH	A value of acidity on a logarithmic scale (base 10) from 0-14. A pH of 7 is neutral, while a pH of 0 is highly acidic and 14 highly alkaline.
PPM	Parts Per Million. A measure of the concentration of an element or molecule as a ratio.
SE	Standard Error. A measure of the variation in samples from a treatment (amendment) mean (average). Small standard errors suggest that the mean accurately reflects the treatment whereas a large SE indicates that the mean may not be an accurate reflection of the treatment.
SPSS	Statistical Package for the Social Sciences. A computer program used for statistical analyses.