GREEN MINES GREEN ENERGY: ESTABLISHING PRODUCTIVE LAND ON MINE TAILINGS

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ABSTRACT

The CANMET Mining and Mineral Sciences Laboratories (CANMET-MMSL) of Natural Resources Canada, Ottawa, has established a consortium initiative entitled “Green Mines Green Energy”. The consortium is composed of representatives from mining, forestry, government, academia and the private sector. The goal is to expand the practice of mine reclamation by furthering the use of organic residuals for the rehabilitation of mine sites - to the extent that they can be used to establish feedstock for the production of biofuels. There is increasing pressure on industry and municipalities to divert clean organic waste materials from landfill and to establish productive uses for them. In many areas of Canada, these materials (particularly municipal SSO compost) are in reasonably close proximity to mines, and may offer a relatively stable, long term, beneficial disposal strategy. Laboratory studies are underway to investigate the potential impact of these materials on tailings oxidation and effluent chemistry, as well as the effect of biosolids/compost-derived dissolved organic carbon on effluent treatability and toxicity. The construction of several half-hectare field plots began on mine sites in 2008. This paper provides an overview of the Green Mines Green Energy initiative and a summary of laboratory and field testing undertaken to date. Overall, preliminary results from the column study suggest that sulphate reduction at the tailings – biosolids interface is occurring, and that steady state has not yet been reached after more than 1 year of testing. Furthermore, the addition DOC has had no significant effect on effluent treatability or toxicity.

Introduction

CANMET Mining and Mineral Sciences Laboratories (CANMET-MMSL) of Natural Resources Canada have initiated a research project entitled “Green Mines Green Energy” and established a consortium of parties interested in participating in the research. The overall objective of the initiative is to demonstrate that organic residuals (e.g. municipal biosolids, pulp and paper biosolids) can be utilized to remediate mine tailings and establish an agriculturally productive land use where “energy crops” such as corn, canola, soy, switchgrass and other species can be grown and harvested specifically as feedstock for the production of green fuels.

Partners and collaborators currently include Vale Inco, Xstrata Nickel, Goldcorp Canada Ltd. (Porcupine Gold Mines), Highland Valley Copper, BHP Billiton, Barrick Gold, Cape Breton Development Corporation, St. Marys Paper Ltd., Domtar Inc., Abitibi Consolidated, Agriculture and Agri-Food Canada, Ontario Ministry of Agriculture, Food and Rural Affairs, Alberta Research Council, GSI Environment Inc., Laurentian University/MIRARCO, Cape Breton University, the City of Greater Sudbury and Natural Resources Canada.

The potential benefits of this work are numerous and, where conditions are suitable, could represent a significant contribution from the mining industry towards biofuel production, sustainable development and greenhouse gas reductions – including the use of carbon credits. Interest in the development of green fuels has increased tremendously in recent years, and many mining communities across Canada could have sufficient access to organic residuals to further investigate this option. There are many locations across Canada where mining and forestry overlap. Similarly, most major cities are faced with increasing pressure to divert organic wastes from local landfills. Major urban centres such as Toronto can produce very significant quantities of source-separated organic (SSO) compost, but substantial uncertainty remains over long term utilization options for these and other materials. The utilization of these residuals on mine tailings could provide a long term disposal option for many municipalities, while developing tailings areas for agricultural land use.

Covering tailings with organic residuals for the purpose of inhibiting oxygen ingress and tailings oxidation is certainly not a new concept (Pierce, 1992; Stogran and Wiseman, 1995; Tassé et al., 1997; Cabral et al., 1997). However, the intention of the current GMGE research is to take these efforts two steps beyond this typical purpose i.e. to establish commercial crop production on tailings and to contribute towards the production of biofuels.

While tailings impoundment areas have previously been considered as potential sites for growing crops for human or animal consumption, concerns over ingestion of metals or other contaminants that may have been accumulated by the crops have generally prevented this from happening. This is not a concern when the crops are harvested for fuel production, and previous studies in the Sudbury and Elliot Lake area, where papermill biosolids have been used on tailings, have not shown any significant accumulation of metals in the vegetation (Tisch, 2005; Okonski, 2002).

There is an existing body of evidence that substantiates the potential technical and economic viability of using waste organic materials to reclaim mine tailings. For example, in northern Ontario, the successful rehabilitation of the Pronto Mine near Elliot Lake using papermill biosolids (Tisch and Beckett, 1999; Okonski, 2002) was a proving ground for government regulators in Ontario, and opened the door to additional applications in Sudbury (Vale Inco) and in Timmins (Porcupine Gold Mines). Biosolids have also been utilized to a large extent and for a variety of purposes at mine sites in other provinces, including Quebec, Alberta and British Columbia. However, the use of organic residuals to date has been primarily aimed at general reclamation - to control dust and erosion and to improve site aesthetics.

Provincial regulators are increasingly being asked to approve reclamation plans for mining and other brownfield projects involving the use of various wood wastes, with little scientific data available regarding potential impacts. It appears that there is a knowledge gap, particularly in the long term, of the impact of a thick cover layer of organic material (likely be needed to grow energy crops) on the chemistry, mineralogy, hydrology and overall stability of the tailings. The generation of anaerobic conditions combined with the release of a variety of organic acids may increase the dissolution of As, Fe and other metals/metalloids. In addition, the kinetics of tailings stabilization is poorly understood. For example, Pierce et al. (1995) found that municipal compost used as a cover over acid generating tailings produced an iron sulphide precipitate at the compost/tailings interface, but found that reductive dissolution of secondary tailings oxidation products was still occurring at the 290 day point (completion) of the study. It was suggested that this was simply a transitory phase, but recommended that further testing be undertaken to determine if the anaerobic conditions would eventually lead to immobilization of iron, sulphur and trace metals. Thus, there is clearly a need for further detailed, long-term studies of organic cover/tailings interactions, examining a variety of tailings types and disposal scenarios, in addition to examining the feasibility and economics of growing “energy crops” on mine tailings.

While initial project field activities have largely been focused in Ontario, the principal goal of the initiative is to develop similar, cooperative research projects in other provinces and under a variety of conditions (different tailings, disposal scenarios etc.), and to disseminate the findings to communities where this technology may be applicable.

Scope of the Project

CANMET-MMSL aims to establish a research program that is at least 5 years in length and will encompass both laboratory and field investigations. Four (4) main project themes are envisioned:

1) Quantity and Quality of Biomass Produced (e.g. canola, corn)
   - conditions required to maximize growth of energy crops in organic residuals.

2) Impact of the Organic Cover on Tailings and Effluent
   - interaction of various organic covers on tailings porewater, effluent, mineralogy etc.

3) Feasibility Study
   - potential economic/environmental impacts on all relevant sectors e.g. transportation.

4) Communication/Public Education Strategy/Technology Transfer
   - disseminate findings to all stakeholders (including the public and NGO’s) and transfer technology, such that findings can be applied wherever appropriate.

Progress to Date

<u>Column Leaching Study</u>

In November 2006, CANMET-MMSL, initiated a comparative laboratory column leaching study to examine the potential impact of 20 cm and 100 cm covers of papermill biosolids from both St. Marys Paper and Domtar Ltd. over Vale Inco (acidic copper/nickel) tailings as well as Abitibi Consolidated Inc. biosolids over Goldcorp (alkaline gold) tailings (Photo 1). The columns were constructed from 25 cm (10”) diameter clear lexan tubing. A water table was established near the oxidized/unweathered tailings interface and the columns were sampled from the bottom of the column on a monthly basis for the first 12 months and quarterly thereafter. Samples were analyzed for pH, Eh, conductivity, dissolved metals, sulphate, alkalinity, acidity, DOC, nitrate and ammonium. The experimental design incorporates the following scenarios, all run in duplicate:

- tailings control (75 cm oxidized and 25 cm unweathered tailings);
- tailings control plus 20 cm biosolids;
- tailings control plus 100 cm of biosolids;
- biosolids control (100 cm); and
- tailings control plus 20 cm of biosolids mixed with oxidized tailings (for Goldcorp only).

Ten columns were also added to study municipal compost as a cover material and to investigate the impact of liming the tailings prior to placement of the cover.

General observations suggest the occurrence of sulphate reduction. An extensive blackening of the biosolids/tailings interface occurred with the application of 100 cm of Abitibi biosolids (not as prevalent with Domtar or St. Marys biosolids), which is indicative of sulphate reduction (Photo 2).

Photo 1: Overview of Column Set-Up.

Photo 2: Close-up of black precipitate at tailings/organic interface.

This effect was also initially observed in columns containing a 20 cm cover of Abitibi biosolids, but has since disappeared – likely because of oxygen entry as the biosolids dried between wetting cycles. Similar results (blackening) were observed by Pierce et al. (1995), with the black precipitate identified as an iron sulphide.

To date, and despite indications that sulphate reduction is occurring at the tailings/organic interface, there has been little difference observed in the effluent chemistry between the covered and control (tailings only) columns utilizing copper tailings from Vale Inco (Figure 1: pH and nickel). There are potentially two main mechanisms occurring within the tailings as reducing conditions develop below the organic covers. The first is reductive dissolution of secondary mineralization (oxidation products) contained largely within the oxidized tailings, and the second is sulphate reduction – which converts mobile iron and metals to more stable sulphide forms. It is expected that over time, metal and sulphate levels from the columns containing organic covers, especially those with a 1 metre cover, will decline.

It is also apparent (Figure 1) that while substantial concentrations of carbon and ammonium ion (particularly from the St. Marys biosolids) are being generated by the biosolids, it has not (yet) migrated through the tailings.

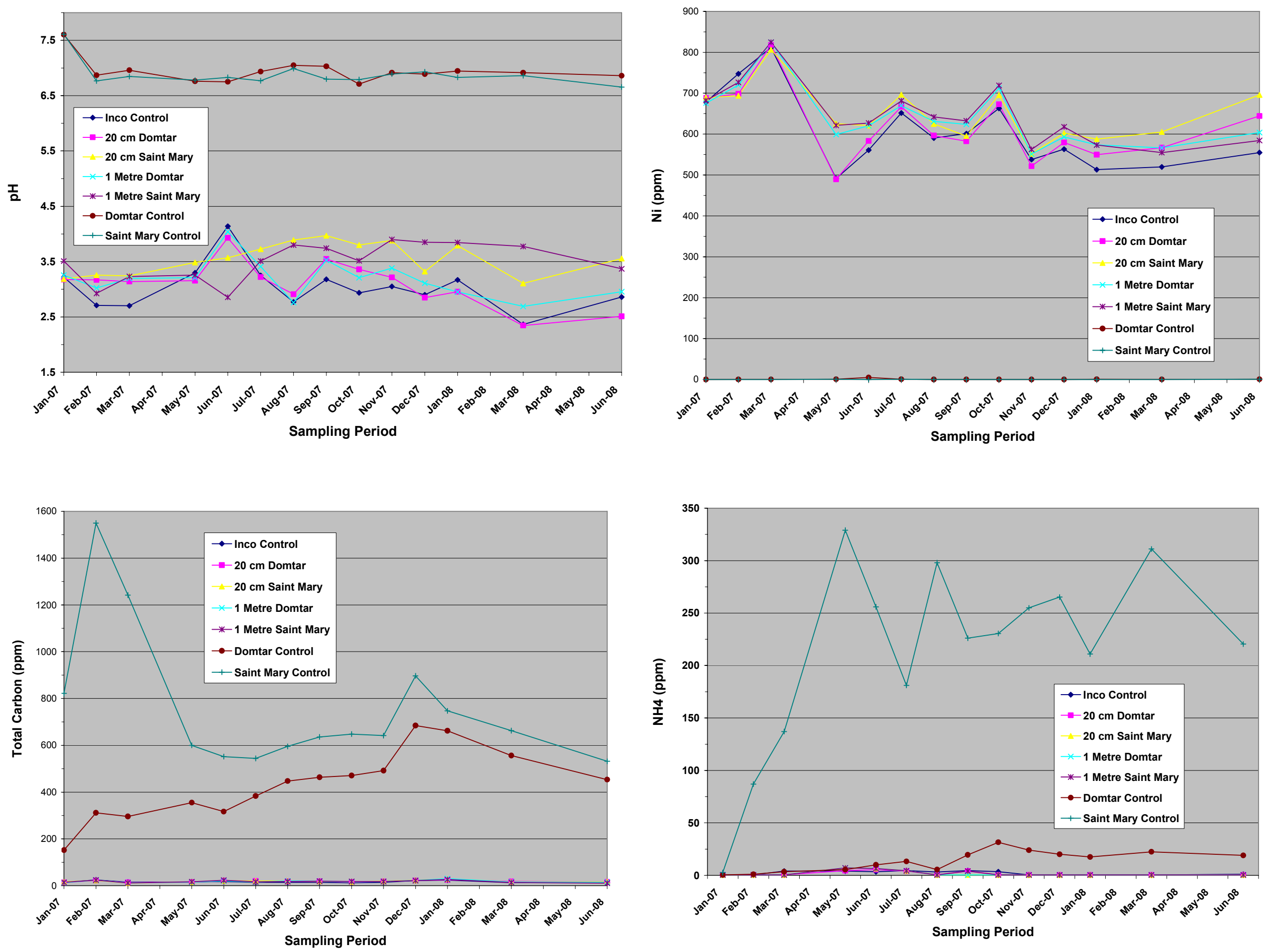

Figure 1: Sample plots of pH, nickel, total carbon and ammonium ion in effluent from columns utilizing unlimed copper tailings from Vale Inco compared with columns containing biosolids only. Example: “1 metre Domtar” refers to a 1 metre cover of Domtar biosolids over copper tailings, while “Domtar Control” refers to a 1 metre depth of Domtar biosolids with no tailings.

Given the large volume and depth of tailings in the columns, it is expected that it will take considerable time for the existing oxidation products to be flushed out of the oxidized and unweathered tailings, so that treatment effects can be observed in the effluent. Furthermore, it is likely that a considerable portion of the available carbon and ammonium ion is being consumed by sulphate reducers and other microflora near the tailings interface.

Arsenic mobilization was evident in the column tests with the gold tailings. Figure 2 illustrates examples of effluent quality from columns containing alkaline gold tailings and a biosolids (Abitibi) control. As noted above, there has been little/no effect on pH, and significant concentrations of carbon generated by the Abitibi biosolids, which has not yet migrated through the tailings. However, these tailings contain residual arsenic, which is being rapidly re-mobilized with the addition of the biosolids cover – at both a thickness of 20 cm and 100cm. This is presumably due to reductive dissolution of oxidation products in the tailings – particularly arsenic sorbed to iron oxides. Microbial activity may also play a role in the arsenic release. Further study is planned to determine the relative contributions.

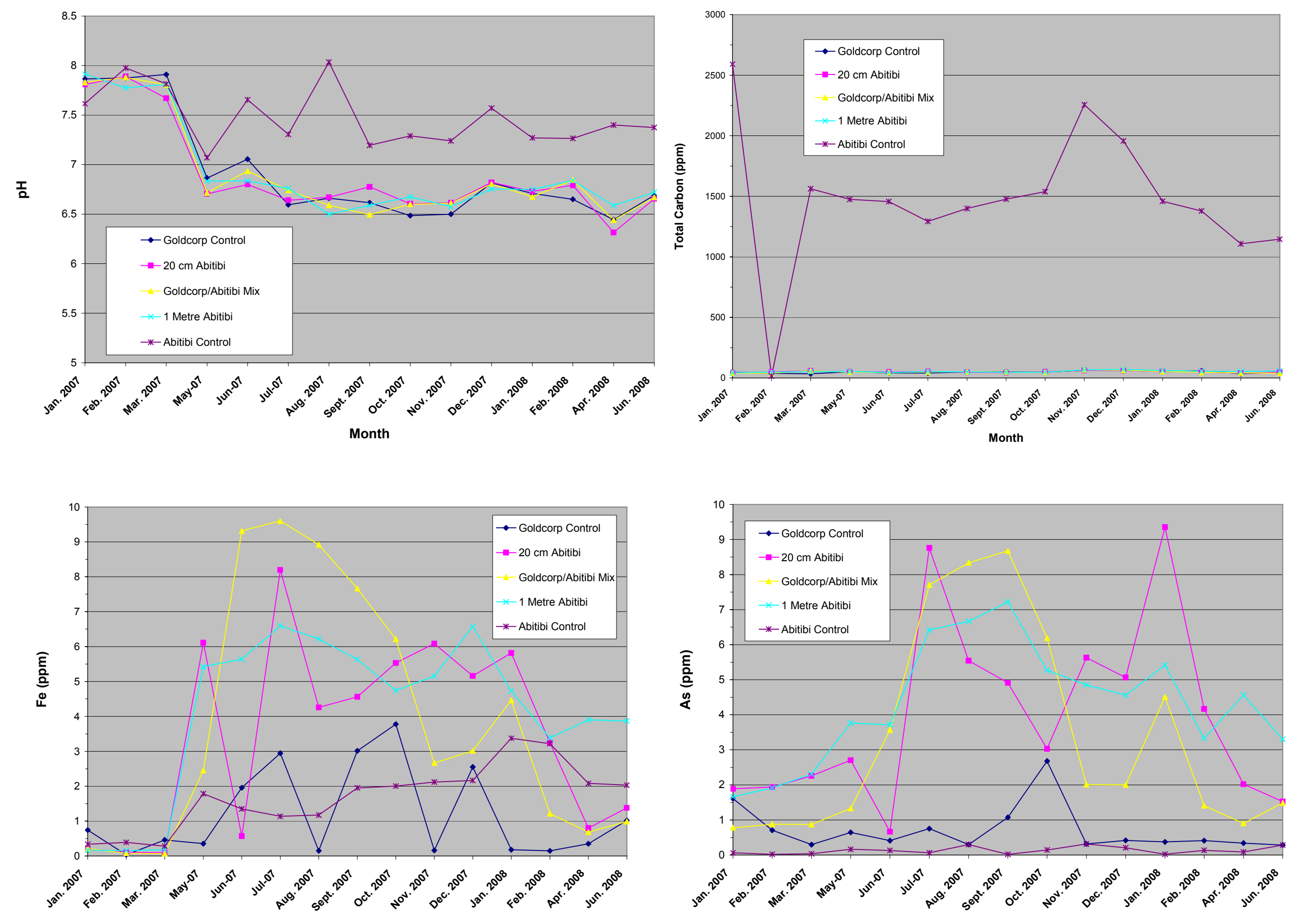

Figure 2: Plots of pH, total carbon, iron and arsenic from columns utilizing alkaline gold tailings from Goldcorp Canada. Example: "1 metre Abitibi" refers to a 1 metre cover of Abitibi biosolids over gold tailings, while "Abitibi Control" refers to a 1 metre depth of Abitibi biosolids with no tailings.

The columns will remain operational until at least January 2009, in order to observe longer-term interaction with the tailings at depth. At termination, they will be destructively sampled to compare mineralogical, trace metal and organic carbon profiles resulting from various treatments.

Effluent Treatability and Toxicity

In order to address concerns regarding the potential for increased dissolved organic carbon (DOC) levels in seepage and surface drainage as a result of adding organic covers, and their impact on effluent treatability (lime treatment and settling) and toxicity, laboratory testing was initiated.

Effluent Treatability

The objectives of this study were to assess the degree of impact (if any) that the application of papermill biosolids may have on treatment of the Copper Cliff effluent.

Batch neutralization tests were utilized to simulate the conventional lime/ air treatment system used by Vale Inco at Copper Cliff, Ontario. To simulate treatment of raw water containing various concentrations of papermill biosolids leachate, samples of St. Marys and Domtar papermill sludge were leached with distilled water to produce a leachate of known (measured) total organic carbon (TOC) concentration. The undiluted St. Marys and Domtar leachate contained 209.3 mg/L and 37.3 mg/L TOC, respectively. This full-strength leachate was mixed with pH-adjusted Copper Cliff raw water to give various final TOC concentrations ranging from 0 – 42 mg/L. The samples with varying concentrations of TOC were then subjected to lime treatment, in duplicate, simulating conditions at the Copper Cliff wastewater treatment plant.

All neutralization tests utilized hydrated lime to achieve a final pH of approximately 10.5. Once the target pH was obtained, the test was allowed to continue for 15 minutes. Aeration was applied in all tests. To evaluate the effect (if any) of flocculant addition in the presence of additional TOC from the papermill biosolids, flocculant was used in some tests to aid settling. Most tests were conducted with one litre aliquots. However, some tests were conducted with eight litres of raw water so that the final effluent could be used for toxicity testing (next section).

Samples of the raw water, as well as filtered and unfiltered effluent samples, were submitted for a complete chemical analysis. In addition, pH, redox, conductivity, and temperature and lime consumption were monitored during treatment. The sludge generated was evaluated for settleability, solids content and production. The results of the neutralization tests are presented in Table 1.

The raw water collected from Copper Cliff (prior to treatment) was of low-strength and did not contain enough sulphate to produce gypsum. As such, the solids production resulting from the water treatment was low; on average 0.33 g/L (kg/m3). In general, the addition of the papermill leachate did not alter the sludge production or the lime consumption to any significant degree.

The sludge produced in this study was of very low density with approximately 1% solids. In addition, the sludge was very difficult to settle. The settling did not improve with the addition of flocculant (Flopam AN 923SH at 2.5ppm). After a 24 hour settling period, some of the sludge appeared to resurface and float on the surface of the effluent.

Table 1: Neutralization test results.

Test #	Leachate type	Leachate Conc.	Retention added Flocculant	Retention Time (min)	Solids Production (g/L)	$Ca(OH)_2$ consump. (g/L)	Slurry[1] Density (%)	Dewatered Sludge Volume[2] (ml)	Dewatered Sludge Density[3] (%)
1-A (blank)	none	0	None	15	---	0.12		34	
1-B (blank)	none	0	Yes	15	0.33	0.16		32	
1-C(blank)	none	0	Yes	15	---	0.17		34	
2	St Marys	5%	Yes	15	0.43	0.13		33	
2-B	St Marys	5%	None	15	---	0.13		31	
3	St Marys	10%	Yes	15	0.30	0.09		24	
3-B	St Marys	10%	Yes	15	---	0.10	0.20	22	1.0
4-A	St Marys	15%	None	15	0.35	0.09		28	
4-B	St Marys	15%	Yes	15	0.35	0.10		31	
4-C	St Marys	15%	Yes	15	---	0.19	0.22	28	1.1
5-A	St Marys	20%	Yes	15	0.28	0.13	---	33	---
5-B	St Marys	20%	Yes	15	---	0.19	---	32	---
6-A	St Marys	5.6%	Yes	15	---	0.11	---	29	---
6-B	St Marys	5.6%	None	15	0.33	0.11	0.20	33	0.7
7	Domtar	5%	Yes	15	0.27	0.12		31	
8-A	Domtar	10%	Yes	15	0.29	0.13	---	31	---
8-B	Domtar	10%	Yes	15	---	0.13	0.21	32	0.9
9	Domtar	22%	Yes	15	0.33	0.13		33	
10-A	Domtar	15.0%	Yes	15	0.34	0.13		32	
10-B	Domtar	15.0%	Yes	15	---	0.13	0.22	31	0.8
11-A	Domtar	19.3%	None	15	---	0.13	---	30	---
11-B	Domtar	19.3%	Yes	15	---	0.12		31	

[1] - Samples were taken from the tank immediately after testing; [2] - Volume was recorded after 24 hours settling of 1L slurry
[3] - % solids was recorded after 24 hours settling of 1L slurry

The sludge produced from both Domtar and St Marys leachate waters contained similar concentrations of most elements. Nickel was present at ~ 6.5% and Fe at ~20%. The St. Marys sludge contained twice as much calcium than was measured in the Domtar sludge.

In general, the metal concentrations in the treated effluent (not shown) were lower in the DOC-amended waters than in the treated control. For example the concentration of nickel was comparable or better in most cases. Lead concentrations were noticeably lower. In some cases the concentration of cadmium was slightly elevated (<1 ppb vs. 9 ppb) with the addition of DOC from the biosolids. The levels of salts (Na, K, Mg, SO_4) were higher in all cases compared to the control.

Effluent Toxicity

Effluent toxicity tests were used to assess the potential acute and sublethal toxicity of biosolids-derived DOC and the impact of this DOC on final effluent toxicity using standard Metal Mining Effluent Regulations test species.

The addition of biosolids-derived DOC (and/or associated contaminants) may have an impact on effluent toxicity to aquatic organisms. At elevated concentrations, it is possible that the biosolid-derived leachate itself could be associated with sublethal and lethal effects. Alternatively, at lower concentrations, biosolids-derived DOC can potentially reduce the final effluent toxicity through metal complexation.

The objective of the ecotoxicity component was to provide an assessment of the potential impacts of a papermill biosolids cover on final effluent toxicity, specifically on acute lethality requirements, effluent quality as monitored by sublethal toxicity and chronic toxicity of copper. Toxicity threshold values were first derived for the aquatic species used under the Metal Mining Effluent Regulation, MMER (DFO 2006). The effects of biosolid leachate at concentrations below the toxicity threshold on treated effluent toxicity to *C. dubia* and *L. minor* were then studied. Finally, the effect of biosolid-derived DOC on chronic toxicity of copper to *C. dubia* and copper speciation were determined.

Exposure solutions were prepared by diluting concentrated leachates with culture/dilution water (depending on the species and test method used). Test concentrations were based on measured total organic carbon, effluent concentration in percent, or based on measured copper concentration. For all toxicity testing, a minimum of five leachate concentrations were used in addition to the controls.

Overall, the collected acute toxicity data suggest that the leachate from the paper mill biosolids will have no significant negative impacts or beneficial impacts on the final effluent quality. No acute toxicity was observed from leachate derived from the biosolids alone, and therefore compliance with provincial and federal acute lethality requirements would likely not be affected by the leachate from the biosolids. The highest concentrations of leachate tested (38 and 70 mg C/L^{-1} for Domtar and St. Marys respectively) were not lethal to rainbow trout or *D. magna*.

The concentration of biosolid-derived DOC expected at the effluent treatment plant as a result of large-scale field application of an organic cover is difficult to estimate, because of the size of the tailings impoundments, dilution factors, carbon consumption etc. However, it is not expected to affect sublethal toxicity, which is used to monitor effluent quality, based on observed test results. The 25% inhibition concentrations, IC_{25} ranged from 5 to at least 104 mg C/L. The most sensitive species, *L. minor* has IC_{25} based on frond numbers of 5 and 23 mg C/L for Domtar and St. Marys leachates, respectively. On the other hand, the least sensitive species for the Domtar leachate was fathead minnows with an IC_{25} of at least 36 mg C/L. For the St. Marys leachate, fathead minnows and algae growth were the least sensitive species with IC_{25} of at least 60 and 104 mg C/L respectively. Assuming effluent DOC from biosolids are in few mg C/L range, no sublethal toxicity is therefore expected from the leachate.

At ~ 3 mg C/L, the leachates had limited or no mitigating effects on treated effluent sublethal toxicity. In the case of *L. minor*, none of the biosolid leachate had a significant effect on treated effluent sublethal toxicity based on growth inhibition measured as frond number and dry weight. For *C. dubia*, the leachate had either no effect or had protective effects on effluent lethality and reproduction inhibitions.

Furthermore, the biosolid leachates on copper sublethal toxicity was similar to that for natural humic substances (Schwartz and Vigneault 2007). Both biosolids had a protective effect on copper lethality to

C. dubia, but only St. Marys had a significant protective effect on reproduction inhibition by copper (Figure 3). At their respective IC_5, the St. Marys leachate had a much greater protective effect against copper lethal and sublethal toxicity than the Domtar leachate. The protective effect could be attributed to complexation of copper by the leachate since copper speciation measurements were conducted on solutions containing the biosolid-derived organic carbon and confirmed that it has a similar copper complexation capacity as natural organic carbon.

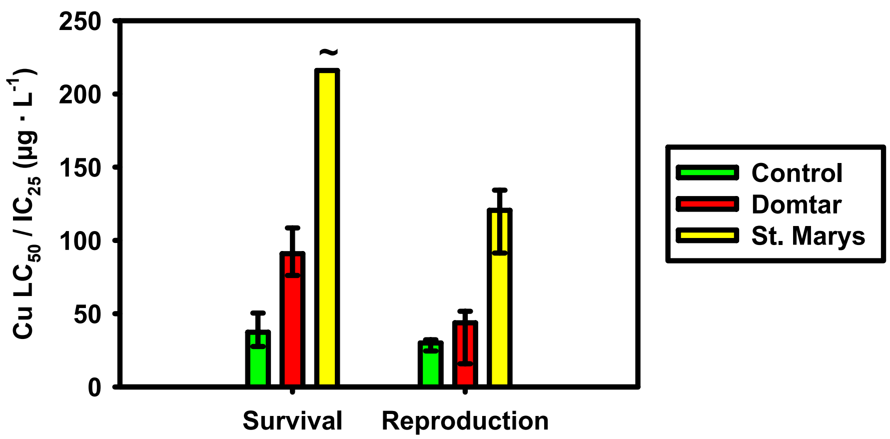

Figure 3: Effect of the Domtar and St. Marys paper mill sludge leachates on copper lethal and sublethal toxicity to *Ceriodaphnia dubia*. Controls were conducted in unspiked M4 medium (Elendt, 1990). The estimated 50 % lethal concentrations, LC_{50}, and the 25 % inhibition concentrations, IC_{25}, are presented along with the upper and lower limits of the 95% confidence intervals.

Field Trials

Field trials were initiated in February 2008 at two locations in Sudbury (Vale Inco) and Timmins (Porcupine Gold Mines). Field plots utilizing papermill biosolids, approximately half-hectare in size to a depth of approximately 1 m, have been established and planted to corn and canola at these locations (Photo 3). Groundwater wells have been installed, and monitoring will include surface and groundwater quality, biomass production and metal uptake by crops. In addition, smaller plots on local agricultural land have also been established in order to compare crop yield on agricultural land with that obtained on the tailings.

Currently, additional test plots are under construction at Vale Inco (second plot), Xstrata Nickel (Onaping, Ontario) and at a Cape Breton Development Corporation site in Sydney, Nova Scotia. It is anticipated that a trial will also be constructed at Highland Valley Copper in spring 2009.

Photo 3: Cultivating papermill biosolids test plots at Vale Inco.

Photo 4: Finished plot at Vale Inco, prior to seeding.

Next Steps

An Advisory Committee has been established and will meet at least annually to review progress and establish research directions. Consortium participants will continue to develop collaborative research projects and identify appropriate funding opportunities. Particular emphasis will be placed on completing construction of the current suite of field trials and on the completion of a 5 year strategic plan.

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Literature Cited

Cabral, A., G. Lefebvre, F. Burnotte, M.F. Proulx, C. Audet, M. Labbé and C. Michaud. 1997. Use of deinking residues as cover materials in the prevention of AMD generation at an abandoned mine site. In: Proceedings of the Fourth International Conference on Acid Rock Drainage, Vancouver, B.C., May 31 – June 6, 1997, pp. 1109 – 1123.

Department of Fisheries and Oceans, DFO (2006) Metal Mining Effluent Regulations. Canada Gazette Part II, 140(21): 1461-1488.

Okonski, A. 2002. Pronto organic soil conditioning: Site monitoring and analyses. Elliot Lake Research Field Station of Laurentian University. Report prepared for Rio Algom Ltd., February 2002.

Pierce, W.G. 1992. Reclamation of sulphide tailings using municipal solid waste compost: Literature review and recommendations. Report prepared for Falconbridge Ltd. by the Centre in Mining and Mineral Exploration Research, Laurentian University, Sudbury, ON.

Pierce, W. G., N. Belzile, and K. Winterhalder. 1995. Reclamation of sulphide tailings using municipal solid waste compost: Laboratory Studies. MEND project 2.25.1(b). Energy, Mines and Resources Canada, CANMET. ON.

Schwartz, M.L. and Vigneault, B. (2007) Development and validation of a chronic copper biotic ligand model for *Ceriodaphnia dubia*. Aquatic Toxicology, 82: 247-254.

Stogran, S.W. and M.E. Wiseman. 1995. A comparison of organic and inorganic covers for long term prevention or amelioration of acid mine drainage. In: Proceedings of the Sudbury'95: Mining and Environment Conference, Sudbury, Ontario, May 28 – June 1, 1995, pp.555 – 563.

Tasse, N., D. Germain, C. Dufour and R. Tremblay. 1997. Organic-waste cover over the East Sullivan mine tailings: Beyond the oxygen barrier. In: Proceedings of the Fourth International Conference on Acid Rock Drainage, Vancouver, B.C., May 31 – June 6, 1997, pp. 1627 – 1642.

Tisch, B. and P. Beckett. 1999. Field studies conducted on the copper tailings at Pronto. Elliot Lake Research Field Station of Laurentian University. Report prepared for Rio Algom Ltd., October 1999.

Tisch, B. 2005. Evaluation of the use of paper sludge and lime for the remediation and revegetation of the CD area of INCO's Copper Cliff tailings. Report prepared for INCO Ltd., Aug. 2005, 72 pp.