Post-Mining Agriculture for Biofuels on Mine Tailings: An Overview of Results from the Green Mines Green Energy (GMGE) Initiative

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Abstract

In 2006, the CANMET Mining and Mineral Sciences Laboratories (CANMET-MMSL) of Natural Resources Canada established a consortium of parties interested in participating in a research program to investigate the potential of utilizing organic materials typically bound for landfill to rehabilitate mine tailings to the extent that they can be used to generate feedstock for the production of biofuels. In partnership with MIRARCO, Laurentian University and other GMGE partners, a research program was developed and implemented on mine tailings at three mine sites in northern Ontario, to assess the potential of growing biofuel crops such as corn, canola and willow on the tailings and the environmental implications of utilizing the organic materials as covers on mine tailings. Four half-hectare size demonstration field trials were constructed from either papermill biosolids or a municipal compost, and monitored for a variety of parameters including crop growth and metal content, groundwater chemistry and metal content in the covers. Results have been very encouraging, with canola growth in some cases exceeding the Provincial (Ontario) average grain yield, indicating the potential to generate enough feedstock for the production of up to 3,600 litres of biodiesel per hectare. No significant long term environmental impacts were observed. An overview of the results from the GMGE initiative will be provided.

Keywords: tailings, organic covers, biofuels, reclamation, energy crops

Introduction

Natural Resources Canada's Green Mines Green Energy (GMGE) initiative is advancing mine site reclamation through the beneficial use of organic residuals for the sustainable establishment of biofuel crops and other productive land uses (Tisch *et al.* 2008). By 1994 estimates, there are more than 41,000 ha of mine tailings in Canada (Feasby and Jones 1994) including 12,000 ha in Ontario and more than 2,500 ha in the Sudbury (Ontario) area alone. Even if only half of the tailings area in Canada were amenable to energy crop production (because of climate, water cover etc.), there is still the potential to develop more than 20,000 ha of "marginal land" for the production of biofuel crops. Further, with increasing municipal demands to divert organic materials from landfill, there are opportunities to utilize these materials for mine reclamation. As a result, the GMGE approach offers an opportunity for the mining sector to significantly improve their sustainability by turning their waste areas into agriculturally productive land. Other benefits would be gained through the production of green energy, reduction in greenhouse gases, and the potential to generate carbon credits through carbon sequestration.

The concept builds on previous successes (Tisch and Beckett 1999) using biosolids to restore tailing areas. However, the establishment of biofuel crops transforms the practice into a potential economically productive endeavour, and offers an alternative to utilizing agriculture grade soil to cultivate energy crops. Growing edible crops in this situation is not feasible because of regulatory issues and potential or perceived health and liability risks associated with food crops grown on metal contaminated wastes. However, energy crops are not destined for human or animal consumption but rather for combustion as biofuels.

Northern Ontario communities in particular can benefit from GMGE reclamation as this area contains the greatest land disturbance from mining in Canada (Natural Resources Canada 2009), but this technology is applicable to mining regions across Canada. The risks associated with residing in proximity to mine tailings areas are usually associated with the environmental and health hazards, but the aesthetic values and opportunities for post-mining economic uses for disturbed mine lands are also important to many communities.

Through GMGE efforts to date, biosolids have been applied as covers (up to one metre in thickness) to accommodate the large root masses of annual energy crops such as canola and corn. Covers also prevent fugitive tailings dust emissions through wind erosion and the thick covers may act as a hydraulic barrier to the tailings, slowing or eliminating water movement to the tailings below (Lock *et al.* 2010). Evidence of the potential for organic covers to act as oxygen barriers has been previously observed (Tasse *et al.* 1997). It is anticipated that the development of a reducing environment at the biosolids-tailings interface, while initially liberating previously oxidized metals (where tailings are already oxidized), will have the long term effect of limiting further sulphide oxidation, acid generation and consequently the release of metals into tailings pore water (Pierce *et al.* 1994, Pierce *et al.*1995).

Initial efforts to establish crops focussed mostly on annuals (corn and canola) and a perennial grass (switchgrass); while more recent efforts focussed on short rotation willow crops. Willow has the potential to generate comparable annual yields (~10 T/ha dw) with little maintenance once established (first 1.5 years) and are harvested on a three year cycle. This offers potential to generate high yield crops at lower cost.

The overarching goal of this work was to demonstrate that biofuel crops can be grown on mine tailings and that organic residuals (wastes) can be diverted from landfill and used as a suitable substrate to facilitate growth of these crops. The research targeted the following four main research themes:

1) Quantity and quality of biomass that can be produced on mine tailings;
2) Impact of organic residuals on mine tailings;
3) Overall feasibility of the approach;
4) Communication, public education and technology transfer

This paper presents an overview of the results of the GMGE initiative, drawing on data from three field test sites.

Materials and Methods

Experimental design

Three tailings disposal strategies have been utilized in the field trials: 1) acidic, oxidized Cu/Ni tailings in direct contact with the organic covers (Vale); 2) acidic, oxidized Cu/Ni tailings covered with a desulphurized "slimes" layer with an organic cover on top of the slimes (Xstrata); and 3) As-bearing alkaline gold tailings in direct contact with an organic cover (Goldcorp).

Vale site (Copper Cliff, Ontario)

In Jan/Feb 2008, a 149m x 21m x 1m biosolids cover was constructed on the Vale Copper Cliff tailings using pulp and paper biosolids obtained from St. Marys Paper (Sault Ste. Marie, ON)). In the spring of 2008, the plot was divided into 4 sections; two sections (replicates) were mechanically sown with Canamaize corn cultivar COPOP1 and two with InVigor 5030 canola. In 2009, this plot was re-planted with the same corn and canola, but was left fallow in 2010. In 2011, the plot was planted with InVigor 5030 canola, to provide data for a third season, and with sunflowers (Pioneer brand 63a21) substituted for corn in the same quadrant design described above.

A second experimental plot was established on the Vale Copper Cliff tailings in 2009. A 130m x 30m x 1m cover was constructed in spring 2009 using pulp and paper mill biosolids from Domtar Ltd. (Espanola, ON). The plot was divided into eight sections for cultivation of 4 crops replicated twice. The crops were mechanically sown with short rotation dwarf Canamaize corn (cv. COPOP1), Hybrid InVigor 5030 canola, and two switchgrass varieties (cv. Sunburst and Cave-in-Rock). The plot was left fallow in 2010. In 2011, this plot was expanded by approximately 3000 m^2 using Domtar biosolids. Canola, switchgrass and sunflower (Pioneer brand 63a21) crops were cultivated. Four 800 m^2 willow plots were established containing four varieties of non-native willows (*Salix Miyabeana* Sx64, *Salix Miyabeana* Sx67, *Salix Sacchanlinensis* Sx61, and *Salix Viminalis*) planted in a Latin Square design. Willows were planted in two pairs of rows with 61 cm between trees, 76 cm between rows, and 152 cm between pairs of rows as per Abrahamson *et al.* (2002).

Goldcorp site (Timmins, Ontario)
During the winter of 2008, a 100m x 50m x 1m plot was constructed on Goldcorp's Delnite tailings using pulp and paper biosolids from Abitibi Consolidated (Iroquois Falls, ON). In the spring of 2008, the plot was divided into 4 sections; two sections were hand sown with Canamaize corn cultivar COPOP1 and two sections with InVigor 5030 canola. These sections were hand sown as the biosolids were too soft for mechanical seeding. In 2009, the plot was completed by expanding to its final dimensions of 110m x 50m x 1m. The plot was then divided into six sections using three crops; each replicated twice, and mechanically planted in early spring. Crops were the canola Hybrid (InVigor 5030) and two switchgrass varieties (Sunburst and Cave-in-Rock). In 2010, the site was left fallow except for the switchgrass crops, which were left to grow for a second season. In 2011, switchgrass was left for a third season, and three 800 m^2 non-native willow plots were cultivated using the same design and varieties as at Vale.

Xstrata Nickel site (Onaping, Ontario)
In late summer of 2008, a 100m x 50m x 1m plot was constructed on Xstrata Nickel's Strathcona tailings using a mixed municipal compost obtained from GroBark (Milton, ON). The compost was a product of composting 10% source separated organics (municipal food waste); 30% leaves; 30% yard waste; 10% aged bark; and 10% small sticks (approximately 1.5cm x 5cm). The plot was cultivated and seeded in spring 2009 with four crops; canola (InVigor 5030), corn (Canamaize COPOP1), and two switchgrass cultivars (Sunburst and Cave-in-Rock), each replicated twice. Crops were set-up in a randomized design within the compost plot resulting in eight sub-plots. In 2010, four treatments were added to the experimental design to determine the cause of poor yields seen in 2009. The four treatments represent combinations of low and high fertilization and ripping to alleviate compaction. The eight plots remained and the monitoring and sampling strategy was maintained. In 2011, the Xstrata experimental plot was expanded by approximately 4250 m^2 using a similar compost product. The experimental design of the original plots was maintained at eight plots, but sunflowers (Pioneer brand 63a21) were substituted for corn. Three 800 m^2 willow plots were cultivated using the same design and varieties as at Vale and Goldcorp.

Plots were seeded and fertilized at standard application rates for each crop. Monitoring included biomass sampling of 1m^2 quadrates to provide yield estimates for each crop. Roots and shoots were also collected for metal and nutrient analyses, and biosolids/compost was sampled at various levels through the profile and monitored for metal content. For willows, survival counts and tree heights were measured mid-season and end of season at each site. Groundwater wells were installed and sampled on a monthly basis, usually between the months of June and November. All samples were digested at 100°C with a concentrated acid mixture (HNO_3:HCl; 5:2), with resulting filtered solutions being analyzed by ICP-AES.

Results and Discussion

1) Quantity and quality of biomass produced on tailings

Biomass production and seed yield for all sites and crops are shown in Table 1. Canola performed well at the Vale and Goldcorp sites, reaching a maximum biomass production of 11 and 9.3 t ha^{-1} respectively. Canola biomass was significantly lower at the Xstrata site, but has tripled in three years, reaching a high of 6.1 t ha^{-1}. The growth substrate used at Xstrata was immature compost with high nitrogen demand, and as such, responded well to fertilizer and performed better as it aged. The decreased biomass production at Vale in 2011 is reflective of an infestation of Lamb's Quarters, a common Ontario weed that has plagued the Vale and Goldcorp biosolids. At 3.3 t ha^{-1} and 2.7 t ha^{-1} in 2009, canola seed yields at Vale and Goldcorp respectively exceeded the Ontario average canola seed yield of 2.17 t ha^{-1} (OMAFRA 2010), at a time when the Ontario average yield was just shy of the record average yield for Ontario. This clearly indicates that economic yields of canola crops are feasible on mine tailings. Corn, while mostly reaching full maturity at the Vale and Xstrata sites, produced a seed yield of only 3.4 t ha^{-1} and 2.5 t ha^{-1} respectively, which was significantly lower than the 9.7 t ha^{-1} Ontario average (GoCorn.net 2010). Corn was planted at the Goldcorp site in 2008, but was entirely consumed by ravens and dropped from further study at the site. The corn was a semi-dwarf variety developed for non-traditional corn growing regions for small grain purposes. Its initial purpose was to showcase a corn field on the tailings, but because of its low seed yield and low sugar content, and thus a low economic value, it was dropped from further study at all sites. It did however produce sufficient biomass to be considered as feedstock for cellulose-based ethanol production; a considerable feat given that Sudbury/Timmins are beyond typical corn growing regions in Ontario.

Table 1: Biomass production (d.w.) and seed yield for various crops at Ontario field sites.

	2008	2009	2010	2011
Vale (St. Marys biosolids) n=10				
Canola Biomass (T/ha)	8.3 ± 2.0	11 ± 2.0	fallow	6.5 ± 2.4
Canola Seed Yield (T/ha)		3.3 ± 0.60		
Corn Biomass (T/ha)	6.4 ± 4.5	9.4 ± 1.5		
Corn Seed Yield (T/ha)		3.4 ± 0.54		
Sunflower Biomass (T/ha)				7.8 ± 2.6
Xstrata n=10				
Canola Biomass (T/ha)		2.1 ± 0.9	4.1 ± 1.4	6.1 ± 2.9
Canola Seed Yield (T/ha)				0.7 ± 0.33
Corn Biomass (T/ha)		0.2 ± 0.2	8.9 ± 3.6	
Corn Seed Yield (T/ha)			2.5 ± 0.73	
Switchgrass Sunburst (T/ha)		0.04 ± 0.02	2.8 ± 1.8	11 ± 1.7
Switchgrass Cave-in-Rock (T/ha)		0.12 ± 0.09	3.4 ± 1.6	9.6 ± 3.5
Sunflower Biomass (T/ha)				7.2 ± 1.7
Goldcorp n=10				
Canola Biomass (T/ha)	7 ± 0.7	9.3 ± 1.7	fallow	
Canola Seed Yield (T/ha)		2.7 ± 0.49		
Switchgrass Sunburst (T/ha)		1.5 ± 1.4	7.4 ± 2.1	7.3 ± 1.0
Switchgrass Cave-in-Rock (T/ha)		1.4 ± 0.9	8.0 ± 4.5	8.7 ± 0.8
Lambs Quarters (T/ha)				8.8 ± 1.3

In an effort to demonstrate the potential utility of perennial species, two varieties of switchgrass were planted at the Xstrata and Goldcorp sites and performed quite well. Switchgrass typically takes three years to reach maturity, which was reflected in our results where it reached a high of 11 t ha^{-1} at Xstrata and nearly 9 t ha^{-1} at Goldcorp in its third year. Switchgrass at the Xstrata site is very dense and has reached a height of nearly 2 metres, while at Goldcorp it has struggled in competition with weeds. Switchgrass is a perennial grass, which grows well in low fertile soils and requires little maintenance once established. This offers a significant advantage in management requirements over crops like canola, which require annual cultivating, fertilizing and seeding.

Sunflowers were seeded at Vale and Xstrata in 2011, both for their aesthetic value and potential as biofuel feedstock. While there was significant variation in plant size across the plots, sunflower performed very well in its first year, reaching a biomass production of 7.8 t ha^{-1} and 7.2 t ha^{-1} at Vale and Xstrata, respectively. Unfortunately, seed yield was not available at the time this paper was prepared.

Field trials were also initiated with various willow varieties in 2011. Short rotation willow plantations are easy to establish in the field through the simple insertion of cuttings into the soil. After the first year of growth, they are cut back to about 5cm height, which promotes the establishment of additional stems (coppices) and therefore much greater biomass production. Weed control is generally only required during the first two growing seasons. Canopy closure after this period controls weeds naturally. Literature values suggest that biomass yields on the order of 10 t ha^{-1} each year after the second season of growth are readily achievable, with very little ongoing maintenance.

Nearly 7,000 willows were planted in total at the GMGE sites. Overall, the highest survival rates were obtained at the Vale site (Domtar biosolids), with survival reaching 92%. Survival at the Xstrata and Goldcorp sites was also good, at between 61 and 85%. Growth (height) during the first season varied by site and variety, with best growth observed in the compost material at Xstrata and reaching heights up to 1.5 metres. The plots will be assessed again in the spring 2012 to determine overwintering survival with heights subsequently measured annually at end of season.

Because of their acidic nature, the tailings/cover scenario at the Vale site probably presents the greatest potential for upward migration of dissolved metals and contamination of the overlying biosolids and is used here to highlight results for metal uptake in both biosolids and vegetation. At the Vale site, copper, nickel and iron are present at much higher levels in the tailings than in the overlying biosolids and can therefore be used as markers for potential contamination. Sampling results for copper, nickel and iron through the biosolids profile and into the tailings are presented in Table 3; no significant accumulation of these metals in the biosolids was indicated over a three-year period, given the error associated with the means. Significant variation in the means (and associated error), particularly near the interface, are likely a result of a combination of mixing of biosolids and tailings during plot construction and the difficulty in discerning the exact interface, leading to the inclusion of tailings particles in the biosolids samples. Apparent enrichment of the surface (0 - 15 cm) samples may be due more to a concentration effect resulting from consolidation and compaction of the biosolids with time, and loss of surface carbon through oxidation. Values for copper and nickel are below the Ontario Typical Range soil concentrations (MOEE 1997) for agricultural land use values of 56 mg kg^{-1} and 43 mg kg^{-1} respectively. However, monitoring of the profiles should continue for several more years to confirm that appreciable accumulation does not occur.

The concentration of Cu, Ni and Fe in the canola shoots does not appear to be increasing with time (Table 4). While Cu and Ni were higher in 2009 compared to 2008, they were lower in 2010. Mean copper concentrations in the canola roots appear to be increasing slightly, but given the error associated with the mean, the increase is modest at best. Nickel and iron do not appear to be accumulating in the roots.

Metal concentration in canola seeds is an important aspect to consider when growing this crop for biofuel purposes, as these metals may affect the quality of the fuel generated. Bell *et al.* (1999) reported copper and iron (nickel not reported) concentrations of 5.0 mg kg^{-1} and 201 mg kg^{-1} respectively in canola seed meal grown in agricultural land at four locations in Canada over several years.

Table 3: Total metal concentrations over time for copper, nickel and iron in the biosolids/tailings profile in the St. Marys biosolids at Vale. (n=4)

	Cu (mg/kg)					
	2008		**2009**		**2010**	
Depth (cm)	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
0 – 15	32.9	6.6	49.5	9.7	47.7	8.5
15 – 30	37.5	12.9	40.4	15.1	41.8	15.7
30 – 45	36.7	24.9	38.6	7.9	41.7	17.8
45 – 60			32.2		26.5	
Interface	102	81.4	137	56.7	36	13.8
Tailings	321	54.9	292	52.1	198.1	58.3
	Ni (mg/kg)					
	2008		**2009**		**2010**	
Depth (cm)	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
0 - 15	15.6	6.3	17	7.6	22.6	7.4
15 – 30	11.6	8.8	12.6	5.4	20.0	11.1
30 – 45	16.1	17.3	8.2	0.6	15.7	4.7
45 – 60			7.7		7.0	
Interface	74.4	85.6	3.9	73.8	15.4	6.0
Tailings	233	83.5	174	16.6	187.3	93.5
	Fe (mg/kg)					
	2008		**2009**		**2010**	
Depth (cm)	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
0 - 15	6005	2190	6986	1310	6088	1596
15 – 30	4944	1717	5923	2422	5305	877
30 – 45	6606	3497	4879	322	5355	335
45 – 60			4751		4020	-
Interface	29175	2701	40705	24693	5070	1624
Tailings	72548	3065	65850	5900	42635	2257

Assadi *et al.* (2011) in a study of three varieties of canola seed, reported a mean value of 11.97 mg kg^{-1} for Cu and a range of 45.2 – 51.7 mg kg^{-1} for iron (Ni not reported). With the exception of copper and iron in 2008, the values obtained for the Vale canola were less than these literature values, indicating that accumulation in the seeds are not currently problematic.

2) Impact of organic residuals on mine tailings

In addition to the effect that the tailings might have on the overlying biosolids, it is also important to investigate the effect of the biosolids on metal retention/release from the tailings in order to be sure there is no significant negative impact.

Groundwater wells were installed at all sites, however, due to dry weather at the Xstrata and Goldcorp sites there was an apparent drop in the level of the water table to below the piezometers and limited groundwater data was collected from these sites. Water levels were less impacted at Vale, and therefore provided the best data available. As noted previously, because the acidic tailings are directly in contact with the biosolids covers, the Vale site presents a more extreme test of metal release than the other two sites and is used as an example of potential impact. In the oxidized Cu/Ni tailings of Vale (and Xstrata), it was expected that the addition of an organic cover would result in an initial release of metals into the groundwater as a result of oxygen consumption by the biosolids and the establishment of reductive dissolution processes in the upper portion of the tailings. At the Goldcorp site, the tailings are oxidized As-bearing alkaline gold tailings and the expectation was that As and Fe in particular would be mobilized as reducing conditions developed.

Table 4: Concentration of copper, nickel and iron in canola shoots, roots and seeds from plants grown in St. Marys biosolids at Vale. (n=10)

	Shoots (mg/kg)					
	2008		**2009**		**2010[1]**	
	Mean	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
Cu	5.90	0.80	4.19	1.77	3.03	0.62
Ni	3.90	3.11	1.18	1.86	1.57	0.12
Fe	85.7	28.0	263	256	27.1	7.20
	Roots (mg/kg)					
	2008		**2009**		**2010[1]**	
	Mean	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
Cu	2.16	1.09	4.04	1.52	7.44	2.37
Ni	1.35	2.41	0.04	0.07	1.41	0.54
Fe	55.4	16.5	39.3	25.6	41.0	13.3
	Seeds (mg/kg)					
	2008		**2009**		**2010[1]**	
Depth (cm)	**Mean**	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
Cu	14.5	20.5	1.60	1.64	3.02	0.53
Ni	16.0	47.1	<0.02	0	1.59	0.50
Fe	110	145	46.5	13.8	23.4	4.70

[1]In 2010, the St. Marys plot at Vale was left fallow, but canola had self seeded (previous years seed). While not monitored for yield, canola samples were collected in the fall of 2010 for metal analyses.

Results for groundwater pH, nickel, iron and sulphate from the plots at Vale are presented in Figure 1. The wells in the Domtar plot were not installed until the spring of 2010, shortly after the plot was completed, and therefore sampling duration was shorter. It is clear that neither the St. Marys nor the Domtar biosolids had a significant effect on near surface (~2.5m) groundwater pH. Initially, pH of the samples was measured in the lab, rather than in the field. This time lag resulted in a lowering of pH through iron oxidation in the high iron-containing samples from Vale, as observed during the period from August 2008 – June 2010. Subsequently, measurements were taken when collected in the field, through an in-line flow system. Elevated concentrations of nickel, iron, and sulphate were observed in St. Marys groundwater compared to the control (uncovered). For nickel, there was a rapid increase in concentration, which peaked after approximately two years then returned to near background (control) after 3 years. Iron behaved similarly, but peaked approximately one year after construction and returned to background levels after approximately 2 years. Sulphate in the groundwater below the St. Marys biosolids was elevated for the first year of monitoring then declined to levels below those observed in the control wells.

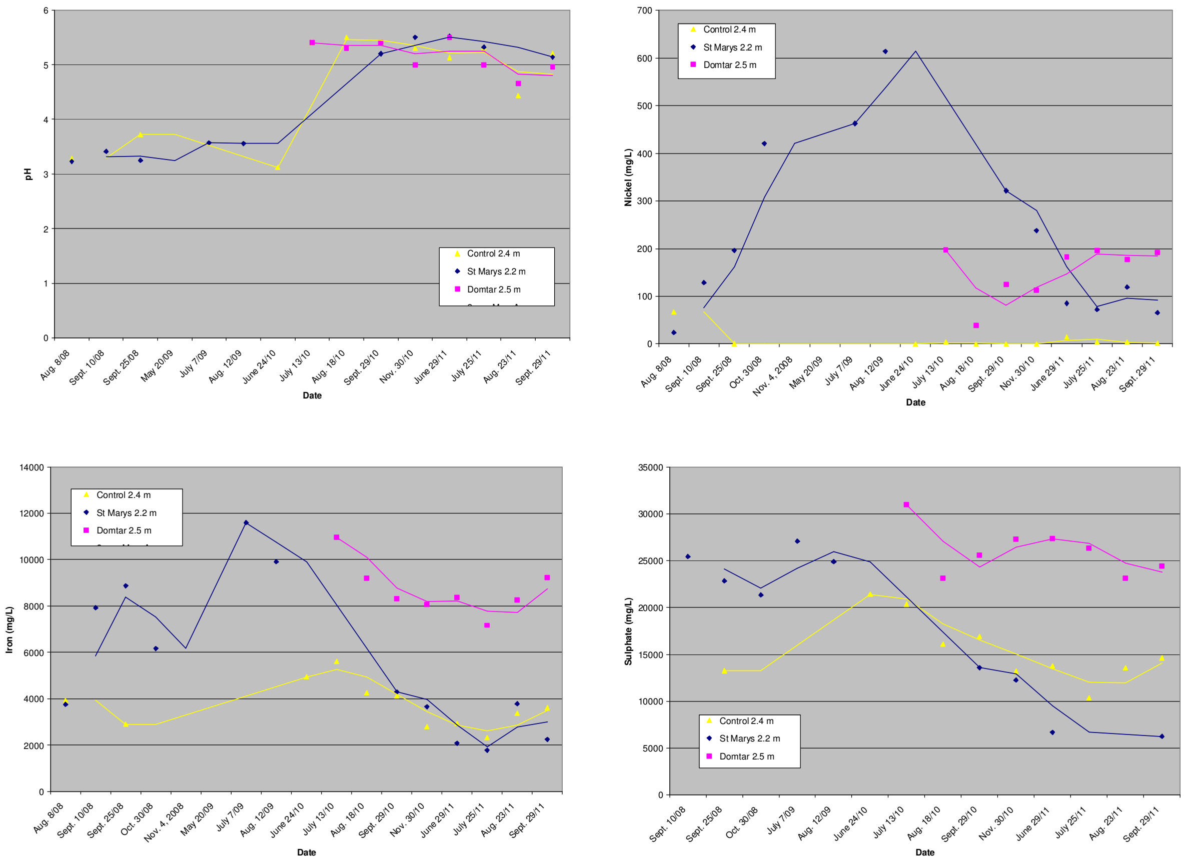

Figure 1: Mean pH and dissolved nickel, iron and sulphate at a depth of 2.2 – 2.5 m in groundwater at Vale. Note: trend lines were added for illustration purposes, based on a 2-point moving average.

Construction of the St. Marys biosolid cover was completed in winter, while the tailings were frozen. Despite this, the haul trucks and spreading equipment undoubtedly caused significant vibration and disturbance/liquefaction in the tailings, creating a plume of enhanced dissolved oxidation products. The control wells were not subjected to such disturbance. The biosolids cover intercepted precipitation, but moisture monitoring showed that it did not prevent water flow to the tailings. Instead, it tended to keep the surface tailings near saturation, suggesting an increase in the downward flow gradient. Evidence of this can be seen in Figure 2, which shows nickel levels peaking successively at greater depth. Over time, nickel concentration declined as lateral groundwater flow flushed the plume away from the sampling wells. While reductive dissolution mechanisms are also likely a factor after the cover is in place, we rationalize that the plume would not be expected to reach a depth of 1.42 metres within a matter of months or up to 3 metres within 2 years through normal infiltration and groundwater flow. Iron and sulphate did not behave similarly to nickel, peaking at similar timeframes at 1.4 and 2.2 metre depths, but then dropping off rapidly to concentrations below those observed at 3.05 metres, suggesting that both are re-precipitating in the tailings before reaching 3.05 metres.

Metals dissolved in groundwater from the Domtar plot are expected to behave similarly, but still appears to be in the initial flushing phase, as it has only been monitored for approximately one year. It is expected that this initial flushing may be of longer duration than occurred for St. Marys, because of significant additional plot disturbance in the fall 2010 as biosolids were hauled by truck through the plot to expand the covered area.

A detailed geochemical investigation is required for the Vale and Xstrata plots to ascertain fully the impact of the covers on the tailings mineralogy.

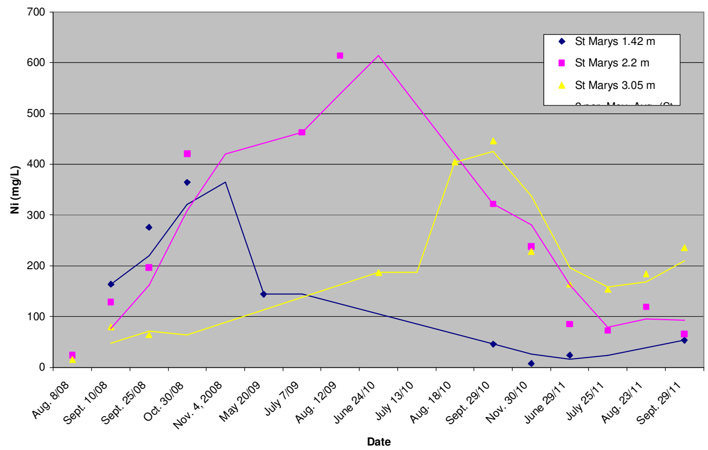

Figure 2: Concentration of nickel at three depths in the tailings groundwater below the St. Marys cover at Vale. Note: trend lines were added for illustration purposes, based on a 2-point moving average.

For the Delnite plot, an initial mineralogical investigation was completed and clearly showed that reductive dissolution of iron oxyhydroxide rims surrounding pyrite grains had occurred, with liberation of arsenic (Paktunc 2011). The reduction front reached a depth of approximately 17 cm into the tailings below the biosolids cover over a period of three years. As a result, As^{5+} had been converted to the generally more mobile and toxic As^{3+}. This was expected, particularly given that the biosolids cover at this site remained a full one metre deep for the duration of the project, and moisture monitoring indicated that it is preventing water from reaching the underlying tailings. Therefore, it appears to be acting as a good oxygen barrier. While groundwater arsenic and iron were expected to increase over time, Figure 3 shows that at a depth of 3.81 metres both in fact, generally declined.

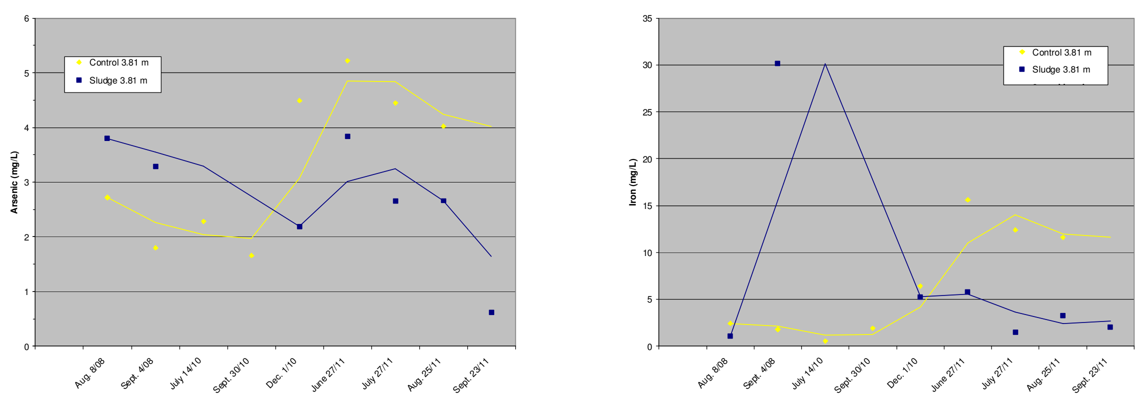

Figure 3: Dissolved arsenic and iron in groundwater at a depth of 3.81 m at Delnite. Note: trend lines were added for illustration purposes, based on a 2-point moving average.

While values relative to the control were probably initially higher as a result of site disturbance during construction as discussed for Vale site, both have trended downwards, reaching concentrations similar to the initial values obtained from the control (uncovered) wells. The mechanism for this appears to be water retention by the biosolids. Despite the increased mobility of arsenic (as As^{3+}) below the cover; it appears that the biosolids are retaining water and decreasing the flushing of the near surface tailings into the groundwater system. The cause of the observed increase in arsenic and iron over time from the control wells is not known, but may be due to a plume of water with elevated concentrations moving down gradient.

3) Overall feasibility

The technical feasibility of applying Green Mines Green Energy types of reclamation to mine tailings was demonstrated. Initial estimates show that while corn was shown to have little economic viability, canola, switchgrass and willow show good potential (Table 5). These values do not include costs associated with establishment of the cover. Further analyses are underway to examine the entire cost cycle, including transportation of cover materials.

Beyond their potential dollar value, the addition of crops to the above mining brownfields improved the biodiversity of the area and their aesthetic value. While not measured, an increase in insects, frogs, rodents, and some larger mammals was observed by researchers. Groundwater metal concentrations under the biosolids cover have shown an initial increase, however it is expected that these will return to background levels once the created agro-ecosystem stabilizes. To date, monitoring of metal mobility within the cover soils and vegetation has shown that the reclamation is safe.

Table 5: Summary of crop yields and potential net revenue for the GMGE approach.

Crop	**Yield ($t\ ha^{-1}$, d.w.)**	**Estimated Biomass Value ($\$\ t^{-1}$)**	**Biomass Revenue ($\$\ ha^{-1}$)**	**Cost of Production ($\$\ ha^{-1}$)**	**Net Potential Revenue ($\$\ ha^{-1}$)**
Canola	3.3 (seed)[1]	488	1610	705	***905***
Switchgrass	11.0[1]	56	616	148	***468***
Willow	10 – 13.4[2]	32[3]	320-429	76	***244-353***

[1]Actual maximum yields obtained from GMGE sites. [2]Estimated yield from Main *et al*. (2007). Note: Cost of production estimates obtained from OMAFRA (2010) for Canola and Main *et al.* (2007) for switchgrass and willow.

Conclusions

The GMGE initiative showed the feasibility of this type of reclamation and demonstrated its many rewards including potential economic return, increased biodiversity and aesthetic value. Major limitations to this style of reclamation are the availability of biosolids in large volumes and the cost of transportation. Future research will examine cultivating crops using shallower covers, and in biosolids-amended tailings to address these limitations. Furthermore, crops that require less maintenance and fertilizer such as perennial crops should be monitored for at least a full rotation to assess their impact on the ecosystem.

The transformation of mining brownfields into agriculturally-productive areas is a major benefit of this type of reclamation and has not been previously demonstrated or achieved. The GMGE reclamation model offers a multitude of benefits beyond creating a productive area, but requires further research to illustrate more fully the safety and sustainability of the reclamation.

The feasibility component of the GMGE project spanned four years, from 2007 to 2010, and demonstrated that the GMGE model of reclamation is technically feasible. Canola, corn, and switchgrass were successfully cultivated at three Northern Ontario mine tailings sites, Vale's Copper Cliff tailings, Sudbury

ON, Xstrata's Onaping tailings, Onaping ON, and Goldcorp's Delnite tailings in Timmins, ON. The crops achieved yield greater than regional averages and in some cases greater than Ontario averages.

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References

Abrahamson, L.P., Volk, T.A., Kopp, R.F., White, E.H., and Ballard, J.L. (2002) The Willow Biomass Producer's Handbook. State University of New York, Syracuse, NY., 31 pg.

Assadi, E., Janmohammadi, H., Taghizadeh, A. and Alijani, S. (2011) Nutrient composition of different varieties of full-fat canola seed and nitrogen corrected true metabolizable energy of full-fat canola seed with or without enzyme addition and thermal processing. Journal of Applied Poultry Research March 2011, Vol. 20 no. 1 p 95-101.

Bell, J.M., Rakow, G. and Downey, R.K. (1999) Mineral composition of oil-free seeds of *Brassica napus*, *B. rapa* and *B. juncea* as affected by location and year. Canadian Journal of Animal Science **79**:(3) 405-408.

Feasby, G. and Jones, R.K. (1994) Report of results of a workshop on mine reclamation. Toronto, Ontario, March 10-11, 1994. MEND Report 5.8e. Viewed 13 March 2012, http://www.mend-nedem.org/reports/files/5.8e.pdf

GoCorn.net. 2010. 2010 Crop Year Report. Viewed 13 March 2012, http://www.gocorn.net/v2006/CornReports/2010cornreport/2010performancetrials.html

Hargreaves, J., Lock, A., Beckett, P., Spiers, G., Tisch, B., Lanteigne, L., Posadowski, T., and Soenens, M. (2011) Suitability of an organic residual cover on tailings for bioenergy crop production: A preliminary assessment. Canadian Journal of Soil Science **92**, 203-211.

Lock, A.S., Hargreaves, J.C., Spiers, G.A., Beckett, P.J., Tisch, B. and Hall, S.T. (2010) From mine wasteland to biofuel cropland – the Ontario experience. In: Proceedings of Mine Closure 2010, the 5th International Conference on Mine Closure, Vina del Mar, Chile.

Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) (2010) 2009 Canola Seasonal Summary. Viewed 13 March 2012, http://www.omafra.gov.on.ca/english/crops/field/reports/2009summary-canola.htm#Summary

Ontario Ministry of Environment and Energy (MOEE) (1997) Guidelines for Use at Contaminated Sites in Ontario. Publication number 3161e01. 186p.

Paktunc, Dogan (2011) Mineralogical characterization and speciation of arsenic in tailings from the experimental field cells at the Delnite mine site. CANMET-MMSL report 11-007 (CR) prepared for Goldcorp Ltd., March 2011, 33 pp.

Pierce, W.G., Belzile, N., Wiseman, M.E. and Winterhalder, K. (1994) Composted organic wastes as anaerobic reducing covers for long term abandonment of acid-generating tailings. *In*: Proceedings of the 3rd International Conference on the Abatement of Acidic Drainage, April 24-29, 1994, Pittsburgh, PA, pp. 148-157.

Pierce, W.G., Belzile, N. and Winterhalder, K. (1995) Reclamation of sulphide tailings using municipal solid waste compost: laboratory studies. MEND Report 2.25.1b, June 1995, 80 pp.

Tasse, N., Germain, D., Dufour, C. and Tremblay, R. (1997) Organic-waste covers over the east Sullivan mine tailings: Beyond the oxygen barrier. *In* Fourth International Conference on Acid Rock Drainage, Vancouver, Canada, May-June, pp. 1627-1642.

Tisch, B. and Beckett, P.J. (1999) Field studies conducted on the copper tailings at Pronto Mine. Report prepared for Rio Algom Ltd. 133 pp.

Tisch, B., Spiers, G., Beckett, P., and Lock, A. (2008) Developing Agricultural Opportunities on Mine tailings: the Green Mines Green Energy Initiative. Presented at the 15th Annual BC MEND Workshop, December 3-4, 2008, Vancouver, B.C.

Zheljazkov, V.D., Vick, B.A., Ebelhar, M.W., Buehring, N., Baldwin, B.S., Astatkie, T., and Miller, J.F. (2008) Yield, oil content, and composition of sunflower grown at multiple locations in Mississippi. Agronomy Journal, **10**(3), 635-642.