CARBON SINK POTENTIAL OF BIOSOLID RECLAIMED MINE TAILINGS

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ABSTRACT

Surface mining can decrease carbon (C) but reclamation can improve soil quality and promote plant growth while restoring the terrestrial C sink. The objective of this study was to determine the effects of biosolids on the C storage capacity of mine tailings over time. Changes in C, nitrogen (N) and plant production over a 13 year period at a deactivated tailings site at Highland Valley Copper mine situated in interior British Columbia, were evaluated. Soil and biomass samples were taken in 2011 and compared to data from a study originally established in 1998. A randomized block design was used and the treatments included a control (no biosolids) and biosolids at application rates of 150 and 250 Mg ha^{-1}. Data was compiled in a chronosequence (representing years 0, 1, 2, and 13 years of reclamation) and analyzed. Biosolids increased total C, N and plant biomass while lowering the C:N ratio. Tailings C concentrations ranged from 1.4% for the control up to 17.2% for the 250 Mg ha^{-1} treatment. Depending on the biosolid application rate, tailings sequestered up to 14 Mg C ha^{-1} yr^{-1} during the 13 years of reclamation. The results show that the use of biosolids during reclamation can improve the C sequestering capacity of mine tailings, which is beneficial to the restoration of the terrestrial C sink and the global C cycle.

Key Words: carbon sequestration, carbon to nitrogen ratio, mine reclamation, municipal sewage sludge

INTRODUCTION

Anthropogenic activities including fossil fuel burning and land use changes, such as deforestation, urban development, agriculture, and mining have contributed to the rise in atmospheric carbon dioxide (CO_2) and other greenhouse gas (GHG) concentrations, causing severe changes in the global climate (Schimel 1995; Shrestha and Lal 2006; Le Treut et al. 2007). Long term atmospheric CO_2 data obtained from ice cores in Greenland and Antarctica has provided evidence showing that the global atmospheric CO_2 composition remained within the range of 280 ± 20 ppm from the end of the Pleistocene (approximately 10,000 yrs ago) to the beginning of the industrial era (late 18th century) (Indermühle et al. 1999). The most recent reading from Mauna Loa, Hawaii shows that CO_2 levels are currently around 394 ppm (an increase of approximately 40%) (National Oceanographic and Atmospheric Administration 2012). Canada is one of the world's leading per capita CO_2 emitters, releasing 16.3 Mt CO_2 per capita in 2008 compared to the global average of 4.8 (World Bank 2012). In 1999, Canada's mining industry contributed approximately 1% (7.3 Mt CO_2) to the nation's total GHG emissions (699 Mt CO_2) (Government of Canada 2002). As of 2007, British Columbia (BC) is a member of the Western Climate Initiative and is committed in legislation, through the *Greenhouse Gas Reduction Targets Act* and the Climate Action Plan, to reduce their GHG emissions by 33% below 2007 levels by the year 2020. Successful revegetation of some of this land can provide meaningful contributions to these GHG emission reduction goals.

Carbon (C) sequestration is the process where atmospheric CO_2 is transformed into plant biomass through photosynthesis and stored in soils as soil organic carbon (SOC) over time. This process is known as carbon (C) sequestration. The SOC is generally composed of partially decomposed organic matter (OM) originating from plants, animals, and microorganisms. The amount of C stored in terrestrial ecosystems is commonly referred to as the terrestrial C sink. Approximately 75% of the global terrestrial C sink is contained in soils as SOC, with the remainder being stored in above ground biomass (Houghton et al. 1985). Average rates of C sequestration over all ecosystems worldwide vary, but are estimated to be 24 kg ha^{-1} yr^{-1} in total (Schlesinger 1990).

In terrestrial ecosystems, soil development occurs as a function of climate, biota, parent material, topography, and time. Surface mining operations cause disturbances to terrestrial ecosystems which result in losses of SOC and releases of CO_2 to the atmosphere due to accelerated decomposition of OM (Schimel 1995; Akala and Lal 2001). In one study in south-eastern Ohio, USA, it was estimated that land disturbance from mining caused a 70% decline in the local C sink (Akala and Lal 2001). In contrast, reclamation of abandoned mine sites can replenish the local C sink by promoting plant growth and re-accumulation of SOC, which aids in the mitigation of atmospheric CO_2 (Shrestha and Lal 2006; Trlica 2010; Trlica and Teshima 2011). Further, the emergence of C markets may present economic benefits to mining operations by being able to provide offsetting of GHG emissions. Akala and Lal (2001) concluded that reclaimed coal-mine-soils in south-eastern Ohio, USA have the potential to sequester 50 to 75 Mg C ha^{-1} in the top 30 cm layer in as little as 20 years. The potential of reclaimed mine sites to accumulate SOC depends on factors such as climate, soil properties, vegetation, and management intensity, before and after reclamation (Akala and Lal 2001).

In open pit copper (Cu) and molybdenum (Mo) mining operations, a common disturbance is the deposition of tailings sediments and waste rock piles over large areas of the landscape. Mine tailings provide major challenges to reclamation because of the lack of chemical, physical, and biological attributes essential for plant growth (Guidi and Hall 1984). Traditional reclamation techniques involve the application of fertilizer or stockpiled topsoil on the tailings material, but these methods have been largely unsuccessful in providing adequate conditions for sustained plant growth over long periods of time (Seaker and Sopper 1988). The use of organic amendments such as biosolids (treated municipal sewage sludge) can improve the overall productivity of tailings sites and support the establishment of a permanent vegetative cover (Sopper 1993). Biosolids generally improve soil physical, chemical, and biological properties by providing OM to the soils. The addition of OM from biosolids results in increased availability of macronutrients (nitrogen (N), phosphorous (P), calcium (Ca), and magnesium (Mg)) (Sopper 1991), reductions in the C to N ratio (C/N ratio) (Gardner et al. 2012), increased cation exchange capacity (CEC) (Guidi and Hall 1984), and favourable changes in soil pH (Zebarth et al. 1999). Biosolid-amended soils also experience higher decomposition rates and improved nutrient cycling than traditionally reclaimed soils due to increased organic C concentration and microbial activity (Seaker and Sopper 1988).

Shrestha and Lal (2006) stated that “a key objective in C management research is to enhance the natural capacity of plants and soils to sequester C” (page 782). The potential to improve soil conditions by the use of biosolids may result in enhancing the C sequestering capacity of decommissioned mine tailings sites. This was demonstrated in a recent study, where Trlica and Teshima (2011) showed that biosolid-amended Cu and Mo tailings stored more C in the upper 0-15 cm layer than did conventionally reclaimed soil over an 8-year period. However, information regarding the long term (>10 yrs) effects of biosolids on mine soil quality (Bendfeldt et al. 2001) and C storage capacity (Trlica 2010; Trlica and Teshima 2011) is presently insufficient, thus providing an area of interest for this study.

This study revisits two very similar research sites used in a previous study (Gardner et al. 2010; Gardner et al. 2012) in order to test the hypothesis that biosolid amendments can improve the C storage capacity of mine “soils”, specifically tailings, over the long term.

MATERIALS AND METHODS

Site Description

The study was conducted on the Bethlehem tailings site at Teck-Highland Valley Copper (HVC), an open pit copper-molybdenum mine located approximately 80 km southwest of Kamloops, BC, Canada. The Bethlehem tailings site is one of three decommissioned tailings sites at HVC currently undergoing reclamation. The tailings material at this site has a silt loam texture and originated from a granodiorite ore containing 60% plagioclase, 10% potassium feldspar, 10% quartz, and a combination of other minerals including biotite, hornblende and calcite (Gardner et al. 2010). The mine is located within the Montane Spruce (MS) biogeoclimatic zone (Government of BC, Ministry of Forests 1991), which experiences a continental climate with cold winters and moderately short growing season. Mean annual temperatures in this zone are usually between 0.5 to 4.7 °C, and mean annual total precipitation ranges from 380 to 900 mm. Highland Valley Copper, however, is situated within the drier region of the MS zone and experiences mean annual precipitation amounts of only 387 mm (54% occurring from April to October), and a mean temperature of 9.6 °C during the growing season. Predominant soils for this area consist of Eutric Brunisols and Gray Luvisols (Government of BC, Ministry of Forests 1991).

Experimental Design

The original study site was established in 1998 to assess changes in chemical, physical, and biological characteristics of the tailings in response to biosolid amendments. The site included eight replicates of seven treatments organized in a randomized complete block design. Each plot was 3 by 7 m, with a 1 m buffer zone between adjacent blocks. In August 1998, Class B biosolids from Metro Vancouver were randomly applied to the treatment plots at increasing rates ranging from 0 to 250 dry Mg ha^{-1} in 50 Mg ha^{-1} increments and incorporated into the tailings material and a control and fertilizer treatment. In June 1999, the sites were seeded at a rate of 36 kg ha^{-1} with a mixture of 33.2% pubescent wheatgrass (*Agropyron trichophorum* (Link) Richt.), 7.5% orchard grass (*Dactylis glomerata* L.), 4.0% creeping red fescue (*Festuca rubra* L. var. *rubra*), 14.7% Russian wild rygrass (*Elymus junceus* Fisch.), 34.6% alfalfa (*Medicago sativa* L.) and 5.9% alsike clover (*Trifolium hybridinum* L.), determined by seed weight. For the purpose of the current study, only three of the original treatments (3 treatments with 8 replicates each, a total of 24 plots) were selected for analyses (control (no biosolids) and biosolids at 150 and 250 dry Mg ha^{-1}). These rates represent the standard (150 Mg ha^{-1}) and maximum (250 Mg ha $^{-1}$) operational rates for mine reclamation in BC (Gardner et al. 2012). For simplicity, the biosolid treatments will be referred to as B150 and B250 (biosolids at 150 and 250 dry Mg ha $^{-1}$, respectively) for the remainder of this paper.

Tailings and Biomass Sampling

Tailings and biomass samples were collected in fall 2011, at the end of the growing season. Five random "soil" cores were taken from the 0-15 cm layer of each plot using an Eijkelkamp Auger and compiled into a composite sample. Small subsamples of the tailings samples were taken and weighed then dried for 24 hrs at 105 °C and re-weighed to determine moisture content. Photosynthetic material, such as leaves and shoots were removed and the samples were air-dried to constant weight for approximately 78 hrs. Root scores ranging from 1 to 5 (based on relative increasing abundance) were subjectively determined for each tailings sample as a means to quantify the abundance of root material for each treatment. Samples were oven-dried for 6 hrs at 60°C to complete drying and passed through a hammer mill fitted with a 2mm sieve. Small (approximately 3 tablespoons) subsamples were taken and crushed with a pulverizer (manufactured by TM Engineering, Vancouver, BC). These samples were sent to Agriculture and Agri-Food Canada (Lethbridge, AB) for the purpose of assessing total C and total N content using a modified Dumas method with a Carlo Erba NA2100 analyzer (Tabatabai and Smith 2003).

Plant biomass samples were collected from a representative location within each plot using a 0.25 m^2 quadrat. Current year`s aboveground growth was clipped as close to the soil surface as possible. Samples were placed in paper bags and oven-dried for 24 hrs at 60 °C. Dry weights were measured and extrapolated to on a hectare yield basis.

Data Analyses

Data for the tailings site from 1998, 1999, 2000, and 2011 were compiled to create a chronosequence showing changes in C, N, and C/N ratio for years 0, 1, 2, and 13 after reclamation with biosolids. Plant biomass was analyzed in a similar manner, but only analyzed for years 1, 2, and 13 (as year 0 data was gathered pre-seeding and therefore had no biomass production).

One way analysis of variance (ANOVA) was conducted to determine differences between treatments within the same years and Tukey post hoc analyses was employed to determine which treatment was most effective when there was a significant statistical difference ($p<0.05$). Two sample t-tests were conducted to compare differences between year 0 and year 13 for the same treatments (for biomass results, year 1 was compared to year 13). Total C (mg kg^{-1}) was extrapolated to a per hectare basis for each treatment using the equation

$$\text{Mg C ha}^{-1} = \frac{\text{C (\%) x bulk density (Mg m}^{-3}\text{) x soil depth (m) x } 10^4 \text{m}^2 \text{ ha}^{-1}}{100}$$

(from Akala and Lal 2001) in order to estimate the C sinks. Since no measurements of bulk density were made during the 2011 sampling, the bulk densities from 1999 (Gardner et al. 2010) were used for this calculation. Linear C sequestration rates were determined by dividing the amount of C (Mg ha^{-1}; calculated from equation) from year 13 by the reclamation duration (13 yrs).

RESULTS

Tailings C levels for the years of the study are displayed in Figure 1(a) for the different biosolid treatments. Total C increased significantly from year 0 to year 13 for all treatments (including the control) ($p<0.05$). The most notable increase was for the B250 treatment where total C increased from 7.0 to 17.2% (an increase of 146%). Over the same time period, C increased from 4.7 to 10.6 % in the B150 treatment and from 0.7 to 1.4 % in the control (increases of 126 and 100%, respectively). After 13 years, total C was highest in the B250 treatment followed by the B150 treatment and the control, and each treatment was statistically different from the others ($p<0.05$). Interestingly, tailings C decreased after the first year of reclamation for all treatments (a decrease of 12, 57, and 52% for the control, B150, and B250, respectively). The calculated C sinks were 26.5, 142.7 and 180.3 Mg C ha^{-1} for the control, B150, and B250 treatments, respectively. The linear C sequestration rate was lowest for the control (2.0 Mg C ha^{-1} yr^{-1}), intermediate for the B150 treatment (11.0 Mg C ha^{-1} yr^{-1}), and highest for the B250 treatment (13.9 Mg C ha^{-1} yr^{-1}).

Similar to the changes in tailings C, total N increased significantly over the reclamation duration ($p<0.05$) (Figure 1(b)). Total N increased from 0.02 to 0.04% for the control, 0.60 to 0.90% for the B150 treatment and 0.94 to 1.65% for the B250 treatment. As percent increases, the control was highest followed by the B250 and B150 treatments at 120, 76, and 52%, respectively. After 13 years, total N was significantly higher ($p<0.05$) in the B250 treatment than in the B150 and control with the control having the lowest. Similar to C, total N also decreased after the first year of reclamation, however, N losses were smallest on the control site (-31%), while the B150 treatment experienced the highest losses (-67%) followed by the B250 treatment (-58%).

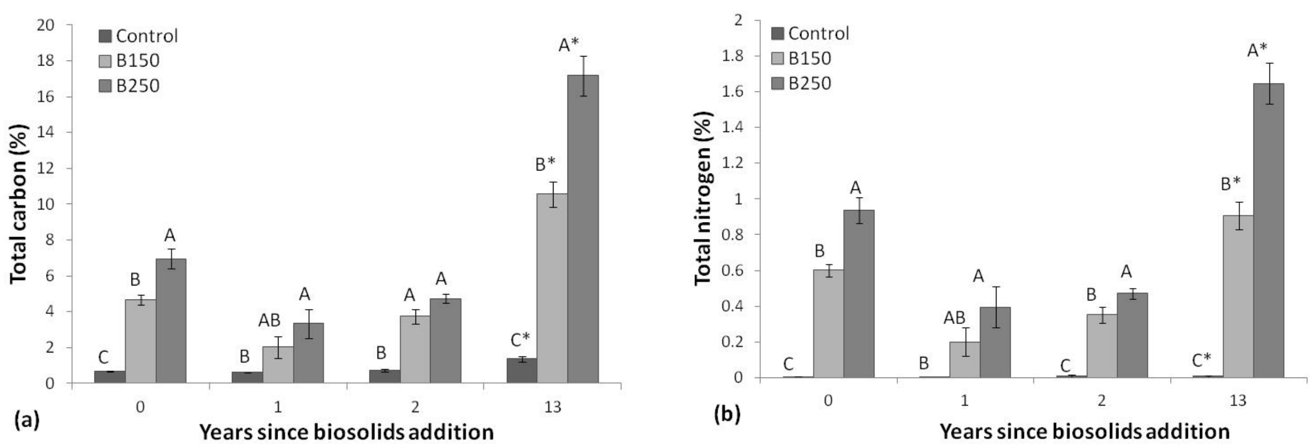

Figure 1. (a) Total tailings carbon and (b) total tailings nitrogen in response to biosolid amendments through 13 years of reclamation. The treatments B150 and B250 represent biosolid applications of 150 and 250 Mg ha^{-1}, control = no biosolids, (n=8 for each treatment). Treatments followed by the different capital alphabetical letters within the same year are statistically significant ($p<0.05$). *Indicates statistical significance between year 0 and year 13 ($p<0.05$).

The C/N ratio for each of the biosolid treatment sites for the years of the study are presented in Figure 2(a). During the first year following biosolid addition, the C/N ratio in the biosolids treatments increased from 49:1 to 60:1 for the control, 8:1 to 24:1 for the B150 treatment and 7:1 to 17:1 for the B250 treatment. Biosolid amendments had a significant effect on the C/N ratio of the tailings as the C/N ratio was considerably lower for the biosolid treatments than it was for the control site in all of the study years ($p<0.05$). The C/N ratio remained lower on the biosolids sites after 13 years (12:1 and 10:1 for B150 and B250 compared to 43:1 in the control). There were no significant differences between the C/N ratios of the two biosolids treatments in any of the study years ($p\geq0.05$). The C/N ratio of the control site showed no significant change from year 0 to year 13 ($p=0.50$).

Plant biomass productivity over the 13 year reclamation period for the control and the biosolid treatments is shown in Figure 2(b). During the first growing season following seeding of the study sites (year 1), plant biomass was significantly more abundant for the two biosolids treatments than for the control (476 kg ha^{-1} and 435 kg $ha^{-1}$for B150 and B250, respectively, compared to 2 kg ha^{-1} for the control). From year 1 to year 13, biomass increased significantly on all sites ($p<0.05$), reaching 388 kg ha^{-1} on the control plots, 6000 kg ha^{-1} on the B150 plots, and 6665 kg ha^{-1} on the B250 plots. After 13 years of reclamation there was a significant difference in plant productivity between the control and the biosolid treatments ($p<0.05$), however, there was no significant difference between the two biosolid treatments ($p\geq0.05$).

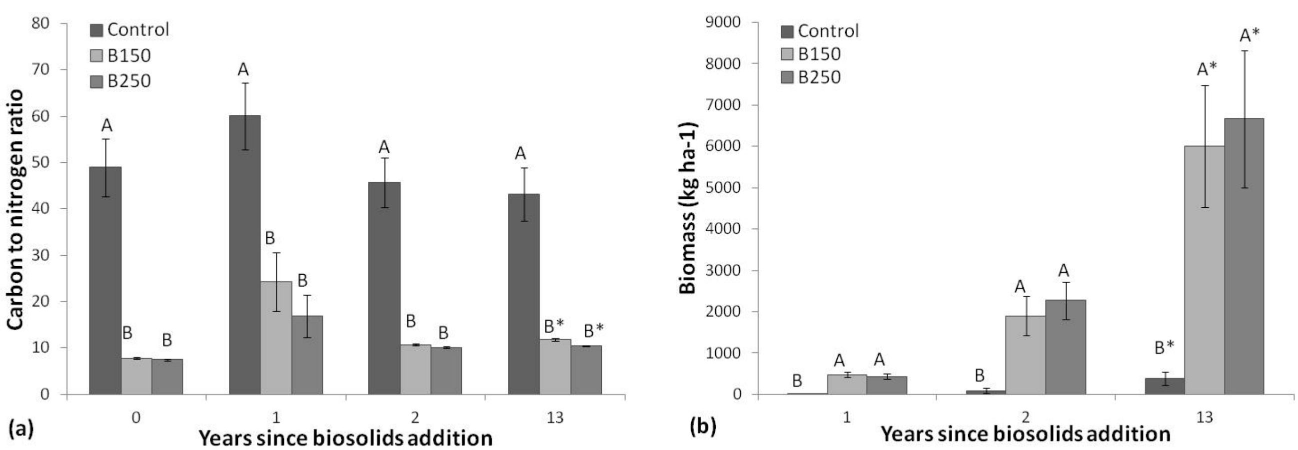

Figure 2. (a) Total carbon to total nitrogen ratio of tailings in response to biosolid amendments through 13 years of reclamation. (b) Plant biomass of tailings sites in response to biosolid amendments through 13 years of reclamation. The treatments B150 and B250 represent biosolid applications of 150 and 250 Mg ha^{-1}, control = no biosolids, (n=8 for each treatment). Treatments followed by the different capital alphabetical letters within the same year are statistically significant ($p<0.05$). *Indicates statistical significance between year 0 and year 13 ($p<0.05$).

DISCUSSION

The results of this study demonstrated that biosolids have a positive effect on the capacity of mine tailings to sequester atmospheric CO_2 over time. This statement is supported by the significant difference between year 0 and year 13 in tailings C concentrations and biomass yields on the sites amended with biosolids (Figures 1(a) and 2(b)). Although the control plots were able to support some plant production, the difference between the biosold treatments and the control in terms of tailings C and biomass were substantially greater.

Carbon Response to Biosolids over Time

Biosolids likely served an important role in increasing the C sequestration capacity of the tailings by enhancing OM content, decomposition rates, and nutrient cycling (Sopper 1993), leading to better soil conditions for plant growth. On all sites, time was a major factor in increasing the C concentrations of the mine tailings. This was consistent with previous other studies (Akala and Lal 2001; Shrestha and Lal 2009; Juwarkar et al. 2010). The observed accumulation of total C over the reclamation period was likely influenced by plant production which, over time, contributed OM to the tailings in the form of roots and litter (Shrestha and Lal 2006; Juwarkar et al. 2010). This is supported by the abundance of above-ground biomass (Figure 2(b)) and roots observed for the biosolids amended tailings sites. Although the control sites showed significant increases in total C with time, the biosolid-amended tailings had a much larger total C concentration compared to the control, which was consistent with other studies (Trlica and Teshima 2011). Moreover, the highest biosolid application rate (250 Mg ha^{-1}) resulted in the highest total C concentration and C sequestration rate indicating that this is the optimum application rate in terms of tailings C storage capacity.

The relative abundance of total C in year 0 for the biosolids sites in relation to the control sites (Figure 1(a)) indicates that the initial carbon source of the tailings was directly obtained from the biosolids. The reduction in total C on the biosolids sites after the first year of reclamation can be attributed mostly to microbial decomposition of the biosolids OM (Gardner et al. 2010). Seaker and Sopper (1988) suspected that biosolids C makes up the majority of SOC during initial years of reclamation, but is eventually replaced by plant biomass C as plant communities establish over time. Such was evident in this study as tailings C at the end of the reclamation period had well exceeded the initial concentrations. This is also supported by the abundance of biomass on site at year 13 compared to that of year 0 (Figure 2(b)).

Nitrogen Response to Biosolids over Time

In this study, biosolids increased the tailings total N concentration when they were incorporated into the tailings material (Figure 1(b), year 0). This initial increase in N suggests that the N originated from the biosolids and is readily available. Once applied to soils, the fate of biosolids N is subject to the N cycle (Pierzynski 1994). The decrease in total N on the biosolids sites after the first year of reclamation may be attributed to leaching, plant uptake of NO_3, volatization (loss of N as NH_3) or denitrification (loss of N as N_2O or N_2). Over time, total N on all sites increased beyond what was initially present in year 0, indicating that these additions in N may have originated from decomposing vegetation combined with the establishment of legumes (e.g. *M. sativa* or *T. hybridinum*) and an active N-fixing microbial community (Sopper 1993). Although the control site exhibited significant increases in total N after 13 years of reclamation, the biosolids sites proved to be most effective at increasing tailings total N, with the highest biosolids application rate (250 Mg ha^{-1}) yielding the best results.

C to N Ratio Response to Biosolids over Time

The application of biosolids prior to seeding reduced the C/N ratio of the tailings to within the optimum range for N availability to plants (<20:1) (Munshower 1994). Without biosolids, the C/N ratio of the control site remained well above the threshold for which N becomes limiting (>25:1). This likely provided better soil conditions for initial plant growth and establishment which was evident from the relative abundance of biomass on the sites with biosolids applied compared the control sites in year 1 (Figure 2(b)). On the biosolid sites, the C/N ratio more than doubled after the first year of reclamation, which was similar to Seaker and Sopper's (1988) findings. The increases in the C/N ratios on all treatment sites after the first year of reclamation likely resulted from the accumulation of plant biomass from the first growing season (year 1). On the biosolid sites, the initial spike in the C/N ratios in year 1 was followed by a notable decrease, then began to equilibrate by the end of the reclamation period, indicating the stabilization of C and N cycles (Sopper 1993). Although the total C and N concentrations at the end of the reclamation period were higher for the B250 treatment than for the B150 treatment, the resulting C/N ratios were comparable for both treatments, indicating that both biosolid treatments examined in this study are capable of stabilizing OM levels over the long term (i.e. >10 yrs).

Biomass Response to Biosolids over Time

SOC levels are directly related to biomass yields due to higher OM inputs with increasing plant productivity. It is safe to say that a productive plant community – in terms of standing biomass – is one outcome of successful reclamation practices. The key to obtaining a self-sustainable plant community that can sequester C over time is to ensure that there is adequate vegetative growth year after year. Such vegetative growth will provide a constant input of OM from dead or dying plant materials on site which in turn will sustain C and N cycling processes and promote soil development (Sopper 1993). The establishment of dense vegetative cover will allow soil moisture and temperatures to be moderated to such an extent as to improve C and N mineralization and nitrification. The presence of an organic soil layer may also improve water retention and infiltration, as well as seed germination success, while preventing erosion (Sopper 1993). Akala and Lal (2001) showed that root growth into the soil profile reduces the bulk density of the soil and provides a major source of SOC input.

In this study, biosolids positively influenced plant productivity. This was likely the result of added nutrients, OM, and ultimately, the transformation of the tailings towards a more well-structured "soil" which had a greater capacity to support plant growth and C sequestration. Although the two biosolids sites did not significantly differ from one another in terms of above-ground plant biomass after 13 years (Figure 2(b)), the B250 site had a higher concentration of total C (Figure 1(a)) and a greater abundance of roots which indicates that, similar to Skousen's study (1988), increasing the biosolid application rate resulted in increases in below ground productivity.

Implications for Carbon Trading

The increased sequestration of GHGs may qualify such emissions reductions as carbon offsets. Afforested lands including mine reclamation sites may also be considered as potential sources for the generation of offset credits (Government of Canada 2008). One carbon offset, or carbon credit, represents one metric tonne of sequestered CO2. To have a financial value, a carbon offset must have a market to sell to.

In BC, the primary carbon offset market is that created by the Pacific Carbon Trust, a Crown corporation that was designed to assist in implementing the Climate Action Plan and to aid government and industry in meeting provincial GHG reduction goals. Under current BC regulations, offset credits generated from approved offset projects can be sold to the Pacific Carbon Trust. Carbon prices are variable in this market, ranging typically from $10-15 as of 2012, though possibly more or less (Chris Adachi, Leader of Energy and Carbon Management, Teck Resources Limited, personal communication, July 24, 2012).

While a Carbon Tax is currently in place in BC, a carbon trading approach continues to be contemplated. If carbon trading were pursued, offsets would likely become an eligible compliance tool, thereby creating a second carbon market where regulated industries would have the option of purchasing and selling offsets to meet their compliance requirements.

Potential benefits exist for mining operations to reduce GHG emissions and generate offset credits on site, either by generating additional income from selling of carbon credits or by applying the generated credits to offset their own emissions. However, in order for this to be feasible, the operation must demonstrate that the reclamation techniques involved in the project be innovative and exceed what is generally required by regulation, a concept known as “additionality”. This might be accomplished with the application of biosolids. This study demonstrated that biosolid amended mine tailings at HVC were able to sequester up to 14 Mg C ha^{-1} yr^{-1} (which is equivalent to 14 carbon credits per hectare per year), depending on the biosolid application rate, which was significantly higher than tailings reclaimed using traditional techniques. Considering that HVC has over 650 ha of reclaimed tailings and over 1700 ha of active tailings, the potential to generate a meaningful amount of carbon credits could exist. Carbon management should be considered in the reclamation plans for HVC and other mine sites around the world.

CONCLUSIONS

This study demonstrated the potential benefits of biosolids for land reclamation to enhance the C sequestration capacity of mine tailings, and allowed us to reject the null hypothesis that biosolids do not increase C storage on mine tailings over the long term (>10 yrs). However, further research will be necessary to assess even longer term effects of biosolids on tailings C storage. This study also contributed to a better understanding of the pedogenic processes that occur over time as a result of biosolid amendments and revegetation of tailings. Further, this study showed that tailings, when reclaimed successfully, will meet the criteria of a developed soil.

It can be concluded that the application rate of 250 Mg ha^{-1} provided the best C storage capacity; however, elevated levels of certain metals may be of ecological concern when this amount of biosolids are used beyond a single application. In terms of initial establishment and long-term productivity of above-ground vegetation, the application rate of 150 Mg ha^{-1} is equally sufficient to the rate of 250 Mg ha^{-1} and is less of a risk in terms of metal concentration.

The findings of this study are of value as it provides a means for estimating the C sinks on tailings sites, and when Canada as a nation reports its GHG inventory for 2012 this study may be of help (Government of Canada 2002b). This study also is of value to HVC and other mining operations by providing direction for reclamation plans that focus on biosolids as a C sequestration tool. The latter may become increasingly critical in consideration of global climate change and the emergence of carbon markets.

Key Findings

- Tailings reclaimed with biosolids applied at 250 Mg ha^{-1} sequestered 180 Mg C ha^{-1} over a 13 year duration, a linear rate of approximately 14 Mg C ha^{-1} yr^{-1}.
- Above-ground plant productivity did not statistically differ between the biosolid application rates of 150 and 250 Mg ha^{-1} after 13 years of reclamation.
- A biosolid application rate of 250 Mg ha^{-1} can produce 14 carbon credits per hectare on reclaimed tailings at HVC.
- Further research is required to assess longer term effects of biosolids on soil development, plant succession, and C sequestration on mine tailings.

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