INFLUENCE OF BIOSOLIDS AND FERTILIZER AMENDMENTS ON SELECTED SOIL PHYSICAL, CHEMICAL AND MICROBIAL PARAMETERS IN TAILINGS REVEGETATION

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ABSTRACT

A three year field study was conducted on two different tailings, Bethlehem (silt loam) and Trojan (sand), to determine the effects of fertilizer and biosolids amendments on selected soil physical, chemical and microbial parameters. Following addition of biosolids at rates of 50, 100, 150, 200 and 250 Mg ha^{-1} soil bulk density decreased linearly. Biosolids addition resulted in an increase in water retention (gravimetric) at field capacity and wilting point but no significant change in water holding capacity were noted. On a volumetric basis water holding capacity decreased with increasing biosolids addition for the silt loam site, but showed no change for the sandy site. Soil pH was generally not impacted by treatment while electrical conductivity, soil organic matter, total carbon and cation exchange capacity all increased with increasing levels of biosolids. Addition of biosolids resulted in an increase in total heterotrophic aerobes, total anaerobes, sulfate reducers, iron reducers and denitrifiers. The chemical fertilizer amendment did not alter soil physical or chemical parameters from that of the control.

INTRODUCTION

Tailings are the materials left after mine processing has removed the mineral ore and because of poor physical and chemical properties and lack of a microbial population are often difficult to revegetate (Munshower 1994). Traditional revegetation efforts have often involved the use of fertilizer additions but studies have indicated that these have a limited effect in speeding soil development and creating a stable, self-sustaining site (Seaker and Sopper 1988, Topper and Sabey 1986, Tate 1985, Stroo and Jencks 1982). Organic amendments have been shown to be useful in improving the soil properties of disturbed areas (Land Resources Network Ltd. 1993). An amendment that is currently gaining popularity is anaerobically treated sewage sludge, more commonly known as biosolids. The addition of biosolids to disturbed sites has been shown to increase vegetation production and promote soil formation with the hope of establishing a self-sustaining site (Seaker and Sopper 1988).

The majority of the studies on biosolids have been related to soil nutrient parameters and metal movement and only a small percentage have addressed the impact of biosolids on soil physical properties (Land Resources Network Ltd. 1993, Metzger and Yaron 1987). In general biosolids application on mine land has been shown to improve spoil material's physical properties resulting in a better growing medium for vegetation establishment and growth (Sopper 1993). Addition of biosolids generally leads to an increase in soil organic matter and total soil carbon (Tester 1990, Glauser et al. 1988, Seaker and Sopper 1988, Visser et al. 1983,Varanka et al. 1976) which can translate into an increase in soil water retention (Zebarth et al. 1999, Tester 1990, Joost et al. 1987, Metzger and Yaron 1987, Hinesly et al. 1982, Gupta et al. 1977, Epstein et al. 1976, Epstein 1975). However, the addition of biosolids has been shown to have conflicting results when calculated as soil water holding capacity for plants, increasing it in some cases (Hinesly et al. 1982) and resulting in no changes in others (Zebarth et al. 1999, Joost et al. 1987, Epstein 1975). Soil texture can also influence how biosolids affects water holding capacity with the organic amendment having greater impact on sandy soils (Metzger and Yaron 1987).

Studies have indicated that the impact of biosolids on water holding capacity is mainly related to the water holding capacity of the amendment itself (Metzger and Yaron 1987) but alterations in soil structure due to sludge application also affect water storage positively. Biosolids additions cause a reduction in bulk density, which translates directly to an increase in porosity (Zebarth et al. 1999, Tester 1990, Joost et al. 1987, Guidi and Hall 1984, Gupta et al. 1977). Martens and Frankenberger (1992) and Joost et al. (1987) demonstrated that biosolids amendments lead to an increase in soil carbon, which in turn increased aggregate formation and improved soil structure. Other studies have also shown that the addition of sludge increased aggregate stability (Glauser et al. 1988, Hinesly et al. 1982, Epstein 1975) by altering pore size distribution (Pagliai et al. 1983).

In relation to soil chemical parameters biosolids additions have been shown to alter soil pH (Zebarth et al. 1999, Brown et al. 1997, Tester 1990, Joost et al. 1987, Topper and Sabey 1986, Guidi and Hall 1984, Hinesly et al. 1982, Griebel et al. 1979, Peterson et al. 1979, Epstein et al. 1976). Increase in electrical conductivity (Tsadilas et al. 1995, Topper and Sabey 1986, Guidi and Hall 1984, Hinesly et al. 1982, Epstein et al. 1976) and cation exchange capacity has been observed. This increase in cation exchange capacity has a direct impact on nutrient retention and on plant growth (Land Resources Network Ltd. 1993). One concern with biosolids is the addition of metals to a site, and this is particularly a concern for mine tailings as often these sites are already high in certain metals.

In terms of the soil microbial community, biosolids has been shown to increase the number of aerobic heterotrophic bacteria versus fertilizer amendment (Sopper 1993). However, very few studies have quantitatively measured the impacts of biosolids on microbial populations and activity. As the establishment of a diverse microbial community is essential to soil formation, studying the microbial community response to amendments is important in determining long-term site sustainability.

There has been an increase in studies investigating selected soil parameters. Only a limited amount of research has been conducted linking the soil physical, chemical, microbial and vegetation responses of biosolids amendments at different application rates as well as comparing these responses to a fertilizer amendment. In 1998 a research project was implemented to study these interrelationships. This paper will only discuss the impacts of fertilizer and biosolids on selected soil parameters to determine the impacts on selected soil physical and chemical parameters, as well as on the soil microbial community within and over a three-year period on both a sandy and a silt loam textured tailing material.

MATERIALS AND METHODS

Study Site Description

The project was conducted on two tailings ponds, Trojan and Bethlehem, at Highland Valley Copper Mine (copper and molybdenum mine) in the interior of British Columbia, approximately 80 km south west of Kamloops and 210 km northeast of Vancouver. Trojan tailings are at 1400 m above sea level and are texturally classified as a sand. Bethlehem tailings are at 1450 m above sea level and are texturally classified as a silt loam. Both sites are relatively flat and border a water body (tailings pond). Over the three years of the study (1998, 1999 and 2000) the yearly average precipitation from April to Oct was 740 mm, the growing degree days were 1174 and the temperature range for April to October was -8.7 to 29.7^{o}C.

Plot Establishment

The study sites were established in the summer of 1998. At each site a randomized complete block design with seven treatments and eight replicates was established. Replicates were added to deal with a moisture gradient and experimental variation. Each plot was 3 by 7 m in size with a buffer strip of 1 m between blocks. The treatments consisted of a control (C0), a fertilizer amendment (F0), and biosolids at rates of 50, 100, 150, 200, and 250 dry Mg ha^{-1}(B50, B100, B150, B200, and B250, respectively).

Anaerobically digested biosolids from the Greater Vancouver Regional District (GVRD) were stockpiled at each site and samples were collected from each to determine chemical composition (Table 1). Biosolids were applied by hand, left for a 2-week period to dry and make it easier for incorporation, and rototilled into the tailings to a depth of approximately 15 cm. In June 1999 the site was broadcast seeded with a grass legume mix containing pubescent wheatgrass (*Agropyron trichophorum*), orchard grass (*Dactylis* *glomerata* L.), creeping red fescue (*Festuca rubra* L. var. *rubra*), Russian wild ryegrass (*Elymus junceus* Fisch.), alfalfa (*Medicago* spp.), and alsike clover (*Trifolium hybridum*). At this time the inorganic fertilizer was manually broadcast on the F0 plots but was not incorporated. The fertilizer contained nitrogen (N), phosphorus (P), potassium (K), zinc (Zn), and boron (B) and was formulated to be similar in total nutrient composition to the B150 treatment based on soil analysis data from the fall 1998 sampling.

Table 1. Selected chemical analysis of biosolids stockpiles.

Variable	Beth	Troj
pH	6.3	6.8
EC (dS/m)	8.1	7.5
total C (%)	29.1	31.3
Dry matter (%)	24.5	23.8

In 1998, prior to application of biosolids, baseline soil sampling was conducted on both sites to test for homogeneity. Soil sampling was conducted in September of 1998, 1999 and 2000 using a random grid and destructive sampling was never located in same area twice.

Vegetation Biomass Data

In 1999 and 2000, 10-1/10th m^2 quadrats were clipped in each plot to determine overall biomass production on a dry matter basis.

Soil Physical Data

Particle size was determined by hydrometer and sieving of the sand fraction (McKeague 1978) and used to classify the soil texture for each site. Bulk density was determined in 1999 and 2000 using the core method as outlined by Blake and Hartage (1986) and one core was collected per plot for 0-15, 15-30 and 30-45 cm depth increments. Time domain reflectometry probes were used in selected plots (F0, B100, B200 treatments on 4 blocks per site) in 1998 to read soil moisture to a depth of 60 cm at 5 cm increments (Topp 1993). Gravimetric soil moisture was also calculated for the top 0-15 cm depth in selected plots (C0, B50, B150, B250 treatments on 2 blocks per site) in 1998 using the oven dry method (Topp 1993). Water holding capacity (WHC) was determined only in 1998 for the top 0-15 cm depth on all treatments and blocks using the pressure plate method as outlined by McKeague 1978. Pressures of 0.01, 0.033, 0.2 and 1.5 MPa were used to produce moisture retention curves for each treatment. WHC was determined by subtracting field capacity from wilting point (1.5 MPa). For Trojan, a sandy site, 0.01 MPa was used for field capacity (Webster and Beckett 1972) and for Bethlehem, a silt loam, 0.033 MPa was used (Jamison and Kroth 1958). Volumetric data was calculated by multiplying the gravimetric data by the 1999 calculated bulk densities.

Soil Chemical Data

Soil core collection for chemical analysis was conducted manually with a hydraulic core (2.7 cm inside diameter) sampler taking five samples per plot at 0-15 cm, 15-30 cm, and 30-45 cm depths. The five cores were then placed in one bag as a composite sample for each plot at each depth. Samples were air dried and passed through a 2 mm hammer mill sieve prior to chemical analysis. Chemical analysis was conducted on samples from all years, all treatments and all depths, except for soil organic matter, which was only analyzed in 1998 using the top 0-15 cm.

Soil pH was analyzed using 0.01 M $CaCl_2$ but samples were left to equilibrate for one week prior to reading (Hendershot et al. 1993a). Salinity was measured by reading electrical conductivity following the method outlined by Janzen (1993). Percent total carbon (C) was determined by dry combustion with a Carbo-Erba carbon analyzer (Nelson and Sommers 1996) and soil organic matter content was determined by ashing samples in a muffle furnace at 600^{o}C for 6 hours. Total cation exchange capacity (CEC) and exchangeable cations (Na^{+}, Mg^{+2}, K^{+},Ca^{+2}) were analyzed using the ammonium acetate method at pH 7.0 as described by Hendershot et al. (1993b).

Soil Microbiology Data

Soil for microbial analysis was taken from 0-10cm depth and maintained in an anaerobic environment at 4^{o}C until the analyses took place and sampling was only conducted on B50, B150, B250, C0 and F0 treatments. Samples were analyzed for total heterotrophic aerobes in 1998 and 2000. In 2000 samples were also analyzed for most probable number (MPN) for total anaerobes, Fe, SO_4 and $N0_3$ (Alexander 1982). A standard plate count technique using serial dilutions plated on agar was used for determining the total heterotrophic aerobes (Wollum 1982).

Data Analysis and Interpretation

Statistical analysis was conducted on the baseline samples and showed homogeneity within sites for the majority of the variables but significant differences between sites for all variables. A two-way analysis of variance (ANOVA) was conducted on each site for each year and each depth. If treatment effect was significant pre-planned orthogonal contrasts were conducted. Year effects were studied by using a split-plot design and all statistical analysis was conducted using the proc mixed with random command in Statistical Analysis System (SAS). Analysis on the three different depths was conducted separately and statistical comparisons were not made between depths. Results were considered significant at probability (p) < 0.05.

RESULTS AND DISCUSSION

Vegetation Biomass Data

Results from vegetation biomass sampling showed a significant increase in biomass production with increasing biosolids treatment levels. In 2000, the average biomass production on Bethlehem tailings was 9, 17, 178, and 227 g m^{-2} for the C0, F0, B50 and B250 treatments respectively. At Trojan the average biomass production was much less 0, 0.2, 11, and 45 g m^{-2} for the C0, F0, B50 and B250 treatments respectively.

Soil Physical Data

The Trojan and Bethlehem mine tailings were texturally classified as a sand and a silt loam, respectively. Bulk density (Db) in the top 0-15 cm in 1999 and 2000 showed a significant linear decrease with increasing levels of biosolids (Table 2), supporting findings in other studies (Zebarth et al. 1999, Tester 1990, Joost et al. 1987, Guidi and Hall 1984, Gupta et al. 1977). The normal range in bulk density for a silt loam is 1.0 to 1.6 Mg m^{-3} and 1.2 to 1.8 Mg m^{-3} for a sand (Brady 1990). Bulk densities at both sites are not considered to be limiting to plant growth. The decrease in bulk density with biosolids amendment can be directly related to an increase in porosity. In general, studies have shown that biosolids increases total porosity and can lead to an improvement in soil aggregation (Guidi and Hall 1984).

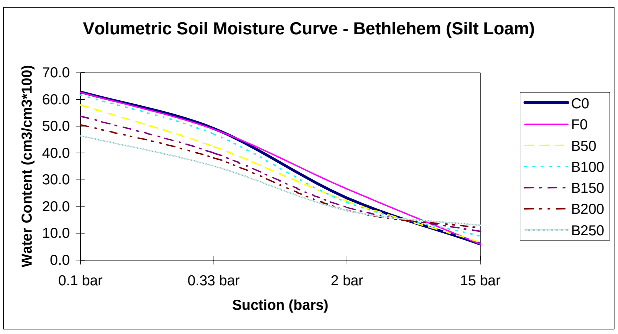
Table 2. Water holding capacity data for 0-15 cm depth (including bulk density (Db) from 1999).

		Gravimetric					Db	Volumetric				
Site	**Trt**	**0.01 Mpa**	**0.033 Mpa**	**0.2 Mpa**	**1.5 Mpa**	**WHC (%)**	**Mg m-3**	**0.01 Mpa**	**0.033 Mpa**	**0.2 Mpa**	**1.5 Mpa**	**WHC (%)**
Beth	C0	50.3	39.4	18.6	4.8	34.6	1.3	62.8	49.1	23.2	6.0	43.1
	F0	50.3	39.2	21.2	4.8	34.4	1.3	62.6	48.9	26.6	6.0	42.9
	B50	51.0	36.6	18.6	5.8	30.8	1.1	58.0	42.4	22.0	6.7	35.7
	B100	56.5	43.4	20.0	8.1	35.3	1.1	61.7	47.1	21.6	8.9	38.3
	B150	59.5	44.0	21.4	11.8	32.1	0.9	53.8	40.0	19.7	10.7	29.3
	B200	58.7	44.4	21.5	14.0	30.4	0.9	50.6	38.2	18.6	12.1	26.1
	B250	63.6	48.4	25.6	17.8	30.5	0.7	46.4	35.1	18.5	13.0	22.2
	P value	0.0001	0.0006		0.0001		0.0001	0.0001	0.0019		0.0001	0.0001
Troj	C0	7.3	5.0	2.3	1.0	6.3	1.5	10.8	7.4	3.5	1.5	9.3
	F0	7.9	4.7	3.0	1.0	7.0	1.5	11.7	6.9	4.3	1.4	10.3
	B50	9.3	6.3	3.8	2.5	6.8	1.4	12.6	8.4	5.0	3.4	9.2
	B100	10.6	7.4	5.2	4.2	6.4	1.3	13.9	9.7	6.7	5.5	8.4
	B150	14.4	10.2	8.1	6.7	7.8	1.1	16.5	11.6	9.3	7.6	8.9
	B200	17.5	15.0	11.5	9.4	8.2	1.0	16.9	14.6	10.8	8.9	8.0
	B250	23.8	17.4	15.2	13.6	10.1	0.9	21.8	15.9	14.0	12.6	9.2
	P value	0.0001	0.0001	0.0001	0.0001		0.0001	0.0004	0.0005	0.0001	0.0001	

Field soil moisture percent (gravimetric) for the moisture probe data and oven dry method generally showed no treatment effect. The exception was the moisture probe data for the top 0-15 cm in 1998 at the Trojan site which showed a significant increase with increasing amounts of biosolids. Epstein et al. (1976) noted an increase in soil moisture with biosolids treatments > 160 Mg ha^{-1}. The data from our study, although not significant, does indicate increasing moisture content with increased biosolids rates (Bethlehem C0 at 13.8% moisture versus B250 at 24.6% and Trojan C0 at 0.6% moisture versus B250 at

16.3%). The lack of statistical significance is due to the small sample size used to measure both of these variables.

Laboratory pressure plate data indicated that increasing levels of biosolids lead to a significant increase in gravimetric soil moisture in all cases except for 0.2 MPa at Bethlehem (Table 2) which is in agreement to results indicated in the literature (Zebarth et al. 1999, Tester 1990, Metzger and Yaron 1987, Hinesly et al. 1982, Joost et al. 1987, Gupta et al. 1977, Epstein et al. 1976, Epstein 1975). Graphed on a volumetric basis the entire water retention curve at Trojan shifted toward higher water content but the available water holding capacity did not show a significant change (Figure 1). These results were similar to those found by Gupta et al. (1977) for a sandy soil who stated that the majority of the increase in water retention due to the sludge was a result of water that remained in the soil even at high pressures (1.5 MPa) due to increased surface area and so the curve shifted upwards but overall plant available water holding capacity remained unchanged.



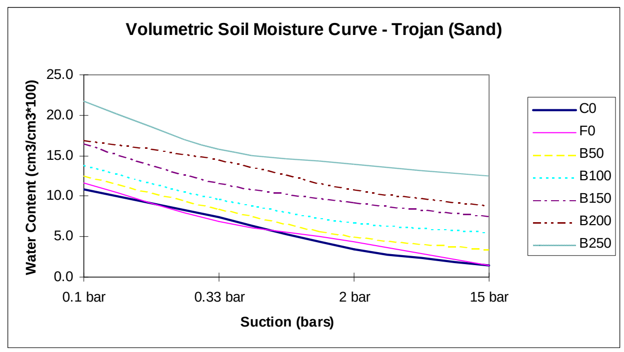


Figure 1. Volumetric soil moisture curves for Bethlehem and Trojan in 1998 at a depth of 0-15 cm (1 bar is equivalent to 0.1 MPa).

The impact of sludge additions on the available water holding capacity of soils is still a subject of controversy (Metzger and Yaron 1987). The results from previous studies have indicated either an increase in available water holding capacity (Hinesly et al. 1982) or no associated change (Zebarth et al. 1999, Joost et al. 1987, Gupta et al. 1977, Epstein 1975). This data is in agreement with our findings at the sandy site but conflicts with our results from the silt loam site. The silt loam site showed a significant decrease in available water holding capacity with increasing biosolids addition when calculated on a volumetric basis (Table 2). The linear decrease in water retention with higher biosolids additions at the lower pressures (0.01 and 0.033 MPa) and then subsequent increase at higher pressures (1.5 MPa) (Table 2 and Figure 1) can be explained by investigating the impact of the organic amendment on the structure of the soil. As mentioned previously, the addition of biosolids decreased bulk density resulting in a direct increase in overall soil porosity. Many studies, however, have demonstrated that the addition of sludge can also lead to increased aggregate stability (Martens and Frankenberger 1992, Glauser et al. 1988, Joost et al. 1987, Hinesly et al. 1982, Epstein 1975) and alter pore size distribution (Joost et al. 1987, Pagliai et al. 1983). At higher suction values, such as at the wilting point (1.5 MPa), the increase in water retention is influenced more by the texture and specific surface of the soil material (Hillel 1982) and thus at both sites is related directly to the increase in overall surface area caused by the organic matter addition (Gupta et al. 1977). At lower pressures pore size will have more of an impact on water retention (Hillel 1982). In sand the pores are relatively large (macropores) allowing for more rapid drainage and lower water retention, while in a silt loam the pores are smaller (micropores) resulting in slower drainage and increased water retention. Addition of biosolids to the silt loam site may have resulted in an increase in aggregation resulting in an increase in larger pores and thus a reduction in water retention with increasing levels of biosolids.

Soil Chemical Data

In general soil pH was not impacted by treatment and average pH over the three years ranged from 7.28 to 7.47 for Bethlehem and 7.04 to 7.29 for Trojan. The pH range considered most favourable for plant growth is 6.0 - 7.2 for most crop plants (Brady 1990). pH is species dependent and crops vary widely in their tolerance to pH (Tisdale et al. 1993). As the pH of biosolids is typically close to neutral, the addition of biosolids to alkaline sites usually decreases pH (Zebarth et al. 1999, Topper and Sabey 1986, Hinesly et al. 1982, Peterson et al. 1979, Epstein et al. 1976) while it increases pH at acidic sites (Brown et al. 1997, Tester 1990, Joost et al. 1987, Guidi and Hall 1984, Griebel et al. 1979). In our study the pH of the biosolids was approximately 1 unit lower (Table 1) than that of the unamended soil; however, the difference was so slight that it did not make a large impact on overall pH levels. In comparing the impact of sludge amendments on pH of sites of different textures Brown et al. (1997) and Tester (1990) both noted a greater pH increase at depth on coarse textured soils. Our results do not indicate any significant treatment by site interactions.

At a depth of 0-15 cm, addition of increasing rates of biosolids resulted in a significant linear increase in electrical conductivity (EC) at both sites (Table 3). This increase in EC with increasing rates of biosolids has been noted by Tsadilas et al. (1995), Topper and Sabey (1986), Hinesly et al. (1982), Epstein et al. (1976) and in a review paper by Guidi and Hall (1984). In 1998, at higher treatment levels, the EC at Bethlehem exceeded the recommended level of 4 dS m^{-1} (Brady 1990). Both Topper and Sabey (1986) and Hinesly et al. (1982) found that EC levels of >4 dS m^{-1} resulted in decreased grass growth; however, the application rates resulting in the increased EC were > 224 Mg ha^{-1} in Hinesly et al. (1982) versus the much lower rates of 83 Mg ha^{-1} for Topper and Sabey (1986). In 1999 the EC levels dropped to below 4 dS m^{-1} and a significant decrease in EC was noted in all 3 years for both sites. These results are similar to those of Epstein et al. (1976) who found higher EC levels in the first year and then a subsequent reduction over time. Therefore, a management application for the Bethlehem site would be to wait one year after application of biosolids prior to seeding, as was done in this study. At depths of 15-30 and 30-45 cm a significant increase in EC was still noted on both sites in most years but all the EC values remained below 1 dS m^{-1}.

Table 3. Soil electrical conductivity (dS m^{-1}) at a depth 0-15 cm for all years.

Bethlehem					**Trojan**				
Trt	**1998**	**1999**	**2000**	**Ave. of years**	**Trt**	**1998**	**1999**	**2000**	**Ave. of years**
C0	1.63	1.40	1.30	1.44	C0	0.06	0.05	0.05	0.05
F0	1.55	1.16	1.35	1.35	F0	0.06	0.06	0.04	0.05
B50	2.07	1.60	1.53	1.73	B50	0.46	0.22	0.08	0.25
B100	2.60	2.19	1.81	2.20	B100	0.84	0.41	0.14	0.46
B150	3.77	2.38	2.19	2.78	B150	1.63	0.58	0.22	0.81
B200	3.98	2.44	1.89	2.77	B200	2.08	0.84	0.33	1.09
B250	4.68	2.89	2.21	3.26	B250	2.78	1.44	0.58	1.60
P value	*0.0001*	*0.0001*	*0.0001*		*P value*	*0.0001*	*0.0001*	*0.0001*	

Soil total carbon at the 0-15 cm depth significantly increased with increased amounts of applied biosolids (Table 4). As the carbon at both sites is low to begin with it can be assumed that the majority of the total carbon resulting from the biosolids amendment is organic and thus an increase in total carbon at these sites is directly linked to an increase in soil organic matter. Soil organic matter was analyzed for directly in only 1998 and the results confirm that organic matter is increasing with the addition of biosolids. The soil total carbon shows a significant decrease after the first year. Seaker and Sopper (1988), Visser et al. (1983) and Varanka et al. (1976) all noted that organic matter content of spoil increased with sludge addition as well as with site age. Seaker and Sopper (1988) attributed this increase to an increase in microbial processes and vegetation cover. However, results from Tester (1990) demonstrated a decrease in organic carbon over the 4.5 years of the study and this was attributed to organic matter decomposition. Therefore, the slight decrease in total carbon noted in the first 2 years of our study can be attributed to decomposition of the biosolids as is indicated by the initial increase in soil microbes. As vegetation was only established in the spring of 1999, the increase in litter accumulation and decomposition was likely not evident in the short time frame of this study. It is believed that the increased biomass production noted on the biosolids amended sites will continue to add to the organic matter on these sites resulting in an increase or stabilization of organic matter overtime. At depths of 15-30 and 30-45 cm a treatment effect was not evident and the total soil carbon ranged from 0.55 to 1.01% at Bethlehem and 0.29 to 0.47% at Trojan.

Table 4. Soil total carbon (%) at a depth 0-15 cm for all years.

Bethlehem					Trojan				
Trt	**1998**	**1999**	**2000**	**Ave. of years**	**Trt**	**1998**	**1999**	**2000**	**Ave. of years**
C0	0.68	0.60	0.73	0.67	C0	0.30	0.29	0.27	0.29
F0	0.62	0.54	0.79	0.65	F0	0.30	0.29	0.29	0.29
B50	1.81	1.20	2.06	1.69	B50	1.17	0.77	0.81	0.92
B100	2.68	1.73	2.95	2.46	B100	1.61	1.47	1.24	1.44
B150	4.67	2.04	3.73	3.48	B150	2.52	1.74	1.97	2.08
B200	5.25	2.32	4.46	4.01	B200	3.83	2.28	2.38	2.83
B250	6.96	3.34	4.74	5.01	B250	5.81	3.44	2.94	4.06
P value	*0.0001*	*0.0002*	*0.0001*		*P value*	*0.0001*	*0.0001*	*0.0001*	

Cation exchange capacity (CEC) reflects the sum total of exchangeable cations that a soil can adsorb and is strongly influenced by soil surface area and organic matter content (Brady 1990). As expected, the CEC at Trojan (sand) was much lower than at Bethlehem (silt loam) due to the lower surface area of coarse textured soils (Table 5). However, at both sites the addition of biosolids led to a significant increase in CEC which can be directly related to the increase in soil organic matter. This increase in CEC is positive with regard to nutrient retention. The base saturation was dominated by Ca^{+2}, with K^{+}, Na^{+} and Mg^{+2} accounting for the remainder.

Table 5. Soil total cation exchange capacity (cmol(+)/kg) at a depth of 0-15 cm for all years.

Bethlehem					Trojan				
Trt	**1998**	**1999**	**2000**	**Ave. of years**	**Trt**	**1998**	**1999**	**2000**	**Ave. of years**
C0	21.3	28.8	65.0	38.3	C0	1.3	8.8	8.8	6.3
F0	21.3	26.3	43.8	30.4	F0	6.3	7.5	10.0	7.9
B50	40.0	46.3	76.3	54.2	B50	20.0	16.3	28.8	21.7
B100	52.5	50.0	71.3	57.9	B100	23.8	27.5	35.0	28.8
B150	81.3	70.0	170.0	107.1	B150	57.5	28.8	53.8	46.7
B200	90.0	78.8	133.8	100.8	B200	47.5	38.8	70.0	52.1
B250	121.3	112.5	161.3	131.7	B250	81.3	72.5	87.5	80.4
P value	*0.0001*	*0.0001*	*0.0001*		*P value*	*0.0001*	*0.0001*	*0.0001*	

Soil Microbiology Data

In 1998 there was a peak in total heterotrophic aerobic activity and by 2000 numbers had declined (Table 6). These results are similar to those found by Sopper (1993) who noted that this increase is likely due to the addition of readily available starches and sugars in the organic matter which are decomposed rapidly. It is likely that the aerobic community in 1998, although higher in number, was less diverse than the aerobic community in 2000 (Sopper 1993). Addition of biosolids also led to an increase in total anaerobes, iron reducers, sulfate reducers and denitrifiers at both sites (Table 6). This change in microbial community has a direct impact on nutrient cycling and future site sustainability. In most cases the addition of fertilizer resulted in little difference compared to the unamended control.

Table 6. Soil microbial data for surface horizon (0-10 cm).

Site	Trt.	Aerobes 1998 (CFU/g)	Aerobes 2000 (CFU/g)	MPN Anaerobes	MPN Fe (iron reducers)	MPN SO_4 (sulfate reducers)	MPN NO_3 (denitrifiers)
		10^5/g	10^7/g	10^4/g	10^2/g	10^2/g	10^3/g
Beth	C0	2.24	5.72	4.23	4.32	1.39	3.77
	F0	1.54	7.92	13.46	2.44	0.18	22.06
	B50	23635.00	8.42	45.22	47.50	3.42	120.42
	B150	30337.50	5.02	118.91	447.08	10.30	282.54
	B250	38400.00	3.47	389.59	607.08	33.44	456.38
		10^5/g	10^5/g	10^5/g	10^3/g	10^3/g	10^3/g
Troj	C0	8.08	97.04	1.00	4.89	3.02	3.38
	F0	1.52	1.38	1.92	1.93	0.35	5.54
	B50	5946.30	290.75	53.75	167.76	4.02	46.48
	B150	7212.50	223.07	79.30	155.87	5.01	110.17
	B250	9062.50	416.19	146.43	255.30	19.83	440.66

Fertilizer versus Biosolids Amendments

For all of the variables investigated in this study, there were no significant differences between the fertilizer treatment and control. In addition, most significant treatment effects also resulted in a significant contrast difference between the F0 and B150 treatments. These findings agree with those of Seaker and Sopper (1988) who compared a sludge amendment (120-134 Mg ha^{-1}) to a one time fertilizer application and noted minimal changes in soil organic matter, organic carbon, nitrogen and overall plant growth for the chemically fertilized treatment. In general, studies have indicated that fertilizer amendments on reclaimed areas may initially increase plant growth but productivity decreases if the annual fertilizer amendment is discontinued. This indicates that the fertilizer amendment has little impact on soil formation and site stabilization (Seaker and Sopper 1988, Topper and Sabey 1986, Tate 1985, Stroo and Jencks 1982).

CONCLUSION

A one-time incorporation of biosolids at five different rates demonstrated that biosolids addition had beneficial impacts on many of the soil physical, chemical and microbial parameters studied. Results indicate that use of biosolids in environmental conditions similar to those at this study site can help to reduce some of the current tailings limitations to plant growth such as low organic matter content and soil cation exchange capacity versus those of the unamended tailings and fertilizer application. However, higher rates of biosolids may raise the soil salinity to a level that may be detrimental to plant growth, especially at establishment (seeding), depending on the initial site electrical conductivity. Leaching of salts did result in a decrease in these levels within one year of application. Application of high rates of biosolids is not recommended for tailings sites with an elevated salinity level. Site location, which is directly related to tailings texture, impacted almost all parameters studied indicating that texture plays an important role in determining response to biosolids amendments. Biosolids addition increased the soil microbe population that relates positively to nutrient cycling and long term soil sustainability. Overall, these results indicate that the addition of biosolids rates up to 250 Mg ha^{-1} can help to improve tailings properties by promoting plant growth and leading to active soil formation. Longer term monitoring of this site should be continued to determine if these initial changes will lead to a stable, self-sustaining soil-plant community.

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