NATIVE PLANT RESTORATION OF BIOSOLIDS-AMENDED COPPER MINE TAILINGS [1]

by

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Abstract. Copper mine tailings are difficult to revegetate due to nutrient deficiencies, high levels of acidity, and potential metal toxicities. An amendment of biosolids could ameliorate these harsh growing conditions through the addition of available nutrients, improvement of physical soil properties (e.g. increased water holding capacity), and possible lowering of toxic metal availability through complexation with organic matter. A study was conducted on mine tailings at Holden, WA to evaluate the effect of an amendment of biosolids on the survival and growth of five native plant species (Sitka alder, big leaf maple, fireweed, w. yarrow, and pearly everlasting). Plots were established in tailings, gravel over tailings (G/T), and biosolids plus gravel over tailings. Each of the native plant species, except maple, had their highest survival in the biosolids-amended plot with 3 species at 100% survival. The biosolids amendment was shown to improve the growth of all species except maple. Fireweed produced 62 times more biomass in the biosolids-amended plot compared to the unamended plot (G/T). Plant analysis revealed a dramatic increase in nutrient content with the amendment of biosolids. Biosolids improved the survival, growth, and nutritional status of native plant species on the copper mine tailings.

Additional Key Words: mine reclamation, sewage sludge, plant analysis, nutrient uptake, revegetation, Alnus sinuata, Anaphalis margaritacea, Achillea millefolium, Acer macrophyllum, Epilobium angustifolium.

Introduction

Copper mine tailings can be difficult to revegetate due to nutrient deficiencies, high levels of acidity, and potential metal toxicities (Neilson and Peterson 1978, Peterson and Neilson 1973). The interactions of these factors can cause extremely harsh growing conditions for vegetation on these sites. An amendment of biosolids could ameliorate these harsh growing conditions by adding available nutrients, improving physical soil properties (e.g. increasing water holding capacity), reducing acidity, and possibly lowering the availability of toxic metals through complexation with organic matter (Zasoski 1981, Pierzynski 1994, Halderson and Zenz 1978, Roberts et al. 1988).

In an extensive review of land reclamation projects using biosolids, Sopper (1993) concluded that biosolids applications improved the productivity and fertility of lands disturbed by mining operations; greater yields were supported by amendments of biosolids than inorganic fertilizers. Results from Schoenholtz et al. (1992) showed that more stable sources of soil N were supplied by organic amendments than inorganic fertilizers. In another review Kardos et al. (1977) also reported increases in yield and crop quality by way of recycling nutrients contained in biosolids through soil-plant systems. Biosolids applications resulted in marked increases in spoil pH and plant dry matter of vegetation grown on acidic mine spoils (Haghiri and Sutton 1982). However, most of these studies utilized agronomic species. There has been relatively little work done investigating the response of native plant species to an amendment of biosolids in the reclamation of copper mine tailings.

Zabowski and Everett (1997) reported increased native plant survival following an amendment of biosolids and gravel over copper mine tailings. Up to 300-fold increases in the growth of fourwing saltbush resulted from biosolids applications to copper mine spoils in a greenhouse experiment

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(Sabey et al. 1990). However, in a Wisconsin study on iron-ore tailings, native, herbaceous-prairie, species displayed little response to fertilization or biosolids amendment (Morrison and Hardell 1982).

Utilization of native plant species in reclamation of mine sites may be desirable for restoration. If the management objective is to restore the existing natural plant community, then the introduction of exotic species is to be avoided (Everett et al. 1990). Native plant species adapted to the climatic conditions of the area, or adapted to lower nutrient requirements, may have advantages over agronomic species in revegetation efforts. Native plant species which show a positive response (e.g. increase in individual growth or population size) following natural disturbance may be particularly well-suited to the environmental conditions on mine tailings piles (e.g. ruderal species, Grime 1979). The objective of this study was to evaluate the effect of an amendment of biosolids on the survival, growth, and nutritional status of five native plant species.

Methods and Materials

Site Description and Experimental Setup

This study was conducted on the copper mine tailings at Holden, WA, elev. 3200' (1000 m). Holden is located on the east side of the Cascade Range on the edge of the Glacier Peak Wilderness (Wenatchee National Forest). The climate of Holden is under a continental influence: winters are long and cold, and snow often lasts into May. The growing season is short, hot, and dry. Holden receives approximately 35 inches (90 cm) of precipitation per year, most of which falls as snow. The site is within the Railroad Creek watershed; a deep U-shaped, glacier-carved valley which drains into Lake Chelan (see map in Scherer and Everett 1998, these proceedings). The valley is surrounded by mountain peaks greater than 9000' (2700 m) in elevation.

In excess of 8 million tons (7×10^6 Mg) of copper mine tailings were deposited in piles up to 150' (45 m) high and cover approximately 80 acres (35 ha). These tailings piles were accumulated over a twenty year period between 1938 and 1957.

In 1991 the tailings piles were covered with a 15 cm layer of gravelly sandy glacial outwash to control blowing dust. This gravel cap also appears to act as a mulch to conserve moisture in the tailings below the gravel. Although the gravel cap over the tailings has abated wind erosion, there were questions regarding its ability to support plant growth. Sand/gravel has very poor nutrient retention and water-holding capabilities, and thus has certain limitations as a growing medium for plants.

Twelve individuals of each of five native plant species were planted in June of 1996 in single plots consisting of 1) tailings only (T), 2) 15 cm glacial outwash gravelly sand over tailings (G/T), and 3) biosolids plus sawdust/woodchips amended glacial outwash gravelly sand (B+G/T). The biosolids were obtained from the Holden village septic system, and were applied in the summers of 1993 and 1995 at the rate of 4.6×10^4 L ha^{-1} and 5.5×10^4 L ha^{-1} respectively.

Plant Materials and Plant Analysis

Five native plant species, 1) big leaf maple (*Acer macrophyllum*), 2) western yarrow (*Achillea millefolium*), 3) Sitka alder (*Alnus sinuata*), 4) pearly everlasting (*Anaphalis margaritacea*), and 5) fireweed (*Epilobium angustifolium*) were selected for planting. These are species which either already grow on the site through natural regeneration or are characteristic of disturbed sites in this area. These early successional species possess morphological and/or physiological adaptations which could prove beneficial for tolerating the harsh growing conditions on the tailings piles at Holden, WA.

Sitka alder is a nitrogen-fixing shrub tolerant of deep snowpack, and commonly occupies disturbed, moist habitat such as avalanche chutes, stream banks, and recently deglaciated terrain (Franklin and Dyrness 1988). Yarrow, fireweed, and pearly everlasting are all herbaceous, rhizomatous perennials. Yarrow is common to dry, infertile soils. Munshower (1993) lists yarrow as having been previously used in revegetation programs in the southwestern U.S. and in the northern great plains. Fireweed is a nitrophilic species that is often abundant following clearcutting, burning, or other disturbance (Strand 1957, Klinka et al. 1989, Dyrness 1973). Pearly everlasting is common to dry, rocky slopes, roadsides, and clearcuts, and is recognized as an indicator of exposed mineral soils (Klinka et al. 1989). Big leaf maple may occupy sites disturbed by logging (Franklin and Dyrness 1988), and grows in abundance along roadsides near Holden.

Fireweed and pearly everlasting were germinated from seed and grown in a 50/50 (by vol.)

sphagnum peat/pumice mix. These two species were transplanted to field plots with this peat/ pumice mix together with an intact root system. Fireweed and pearly everlasting received two light fertilizations (N, P, K, Ca, Mg) in the greenhouse prior to transplanting to the study plots. Bare root Sitka alder seedlings (15cm) were purchased from a northern Idaho nursery, and held in cold storage until planting. Emerging yarrow (incl. small rhizomes) and big leaf maple germinants were dug from a local population and transplanted to the study plots. Some damage to the root systems of these two species occurred during digging which may have affected their capacity for survival and growth.

All plants received supplemental water for the first month. Any plants which died within the first two weeks were replaced. Plant survival and height growth were measured in the field. Height growth is calculated as final height minus initial height. Plants were harvested in September 1996 (max. of 8 of initial 12, or less if fewer than 8 survived). Plant biomass (dry weight) of roots and shoots was determined for all harvested plants. Biomass production is calculated as final biomass minus average initial biomass. Statistical testing of biomass production by species within a treatment was performed utilizing single factor analysis of variance (ANOVA) followed by multiple comparison testing utilizing the Tukey test ("honestly significant difference") as described in Zar (1984).

Nutrient and metal concentrations of roots and shoots were determined for 6 individuals of each species in each treatment. However, nutrient and metal concentrations were not determined for fireweed or yarrow in T or G/T or for maple in any treatment because biomass was insufficient for analysis. Total uptake was calculated as [(final shoot biomass x final shoot concentration) + (final root biomass x final root concentration)] - [(mean initial shoot biomass x mean initial shoot concentration) + (initial root biomass estimate x mean initial root concentration)]. Mean values are given (n = 6). Fireweed initial root N concentration is based upon an assumed shoot:root N allocation ratio of 1.95 (this was the average value calculated from final concentrations).

Soil Analysis

Four surface soil samples (0-10 cm) collected from T, G/T, and B+G/T were air dried and sieved to <2 mm. Soil samples were analyzed for pH (1:1, H_2O), total C and N (autoanalyzer), available phosphorus ($0.03N$ NH_4F + $0.025N$ HCl, Bray and Kurtz 1945), cation exchange capacity (1M KCl), and exchangeable cations (1M NH_4Cl). Soil organic matter is calculated as % total carbon x 1.7 (Nelson and Sommers 1982).

Results and Discussion

Soil Chemical Parameters

Chemical properties of the tailings indicate that it is an extremely poor medium for plant growth (see Table 1). The tailings have an extremely low pH, and very high levels of exchangeable aluminum. Very little organic matter or total nitrogen and no available phosphorus are present in the tailings. Base saturation of the tailings appeared to be erroneously elevated and is not given. The 4:1 ratio of exchangeable Al to Ca in the tailings is very unfavorable to plant growth (Cronan and Grigal 1995, Alva et al. 1986, Rorison 1973). Phosphorus deficiency/aluminum toxicity could be critical growth-limiting factors in the tailings.

Table 1. Soil chemical properties of copper mine tailings, gravel over tailings (G/T), and biosolids amended gravel over tailings (B+G/T).

	Tailings	G/T	B+G/T
pH	3.0	5.2	4.2
Organic Matter (%)	0.10	0.16	6.9
Total Nitrogen (%)	0.01	0.01	0.21
Avail. PO4-P ($\mu g\ g^{-1}$)	0	26	46
CEC (cmol kg^{-1})	1.6	1.6	4.7
Base Saturation (%)	——	18	20
Exchangeable (mmol kg^{-1})			
Aluminum	2.1	0.3	1.2
Calcium	0.5	1.7	6.5
Potassium	1.1	0.7	2.2
Magnesium	1.1	0.2	0.5

Mean values (n=4)

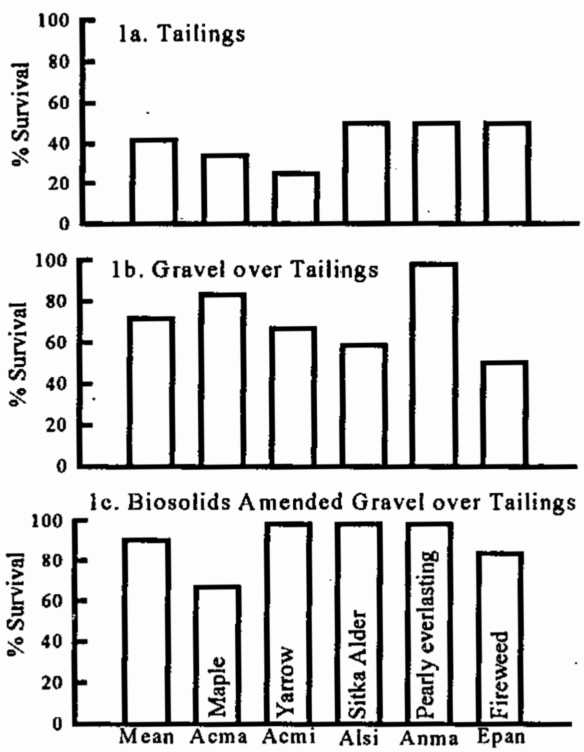
While the gravel over tailings (G/T) had a marked increase in pH compared to T, the material is still lacking in organic matter and total nitrogen. Available phosphate is considerably higher in G/T than in T. Cation exchange capacity is quite low in both T and G/T. Given adequate water, G/T should support plant growth better than T based on an increase in P supply and a reduction in acidity and exchangeable Al.

The application of biosolids to G/T increased organic matter and total nitrogen >40 times that of G/T. Available phosphorus is almost doubled. Exchangeable Ca, K, and Mg and cation exchange capacity are tripled with the amendment of biosolids to

G/T. Chemical analysis of B+G/T indicates it should support increased plant growth. Initial nitrogen losses should have been reduced by the addition of sawdust/woodchips to the biosolids encouraging microbial immobilization. Nitrogen availability can increase in the second year as the decomposition process moves from net immobilization to net mineralization (Bledsoe 1981).

Plant Survival

Figure 1. shows percent survival of each of the five native plant species. In the tailings treatment, half of the area had no survivors of any species. However, the other half had 100% survival of alder, fireweed, and pearly everlasting. Thus, figure 1a depicts 50% survival overall for these 3 species in the tailings. Maple and yarrow had 66.6% and 50% survival, respectively, in the less toxic area of the tailings. Consequently, figure 1a shows 33.3% and 25% survival overall for maple and yarrow, respectively. Differences in plant survival between the two tailings areas may be due to variation in pH (pH 2.5 in high mortality area vs. pH 3.5 in low mortality area) and the effects this increase in H^+ ion activity can have on metal availability (Al, Fe, Mn, Zn). Based on the extremely high concentrations of Fe in solutions of extracted exchangeable cations (data not shown) and the pH of 2.5 it is possible that mortality was due to iron toxicity. Below pH 3.0, Fe^{3+} solubility increases and becomes potentially toxic (Rorison 1973).



Figures 1a-c. Percent survival over one growing season of five native plant species in tailings, gravel over tailings, and biosolids amended gravel over tailings.

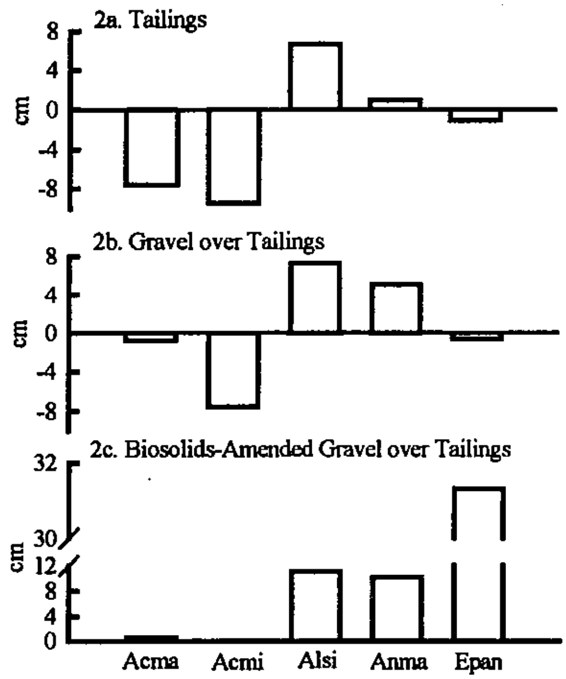
Overall survival was greater in G/T relative to T. Pearly everlasting had the highest survival in G/T (Fig. 1b). This may be due to adaptations for drought tolerance such as pubescent leaves that maintain a more mesic boundary layer and reduce evapotranspiration demand at the leaf-air interface. Survival of fireweed in G/T was the lowest of all species.

Each of the native plant species, except maple, had their highest survival in the biosolids-amended plot with 3 species at 100% survival (Fig. 1c). Sitka alder, yarrow, and pearly everlasting all exhibited no mortality. Mean plant survival of all 5 species increased from 42 to 72 to 90 percent in T, G/T, and B+G/T respectively. The amendment of biosolids to G/T clearly improved native plant survival over that of G/T or T.

Plant Growth

Height. Mean height growth over one growing season is shown in Figure 2. Sitka alder demonstrated a high degree of tolerance of the harsh growing conditions in the tailings. Vertical growth of Sitka alder far exceeded that of any other species in the tailings (Figure 2a). Sitka alder had 7.5 times the height growth of pearly everlasting, the species with the next greatest vertical growth. The success of alder in the tailings probably resulted from tolerance to high levels of acidity and exchangeable aluminum.

At the time of planting, the maple seedlings each had a pair of relatively large leaves. The leaves desiccated and dropped from most of the maple seedlings in T and G/T, many of these, however, were able to resprout a second set of smaller leaves. Transplant shock likely contributed to the susceptibility of the maple (and yarrow) to desiccation. Leaf-drop of maple in G/T was not nearly as prevalent as in T. Fireweed and yarrow also exhibited die-back in T and G/T, with yarrow resprouting in some cases. Negative values represented in figure 2 show the effect that die-back had on mean height growth. Both maple and yarrow displayed a strong propensity for regrowth following initial leaf loss. This capacity for regrowth can be an important attribute for species used in



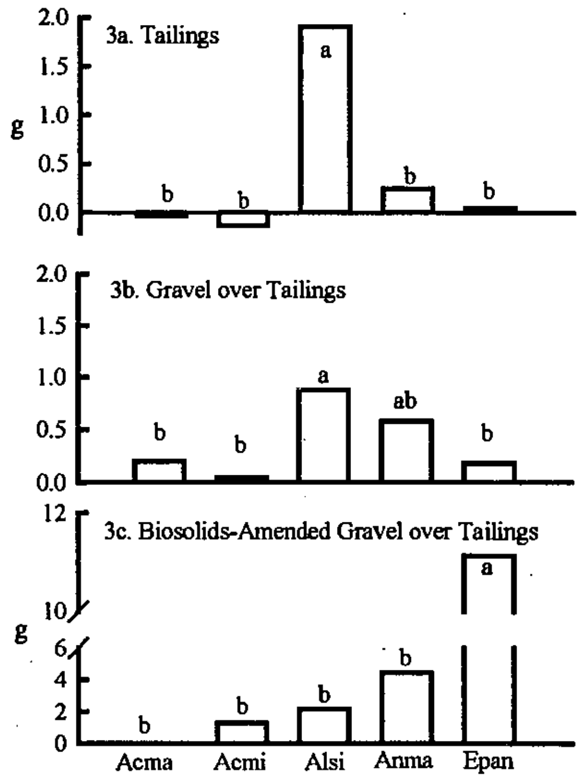
Figures 2a-c. Mean height growth of five native plant species in tailings, gravel over tailings, and biosolids amended gravel over tailings over one growing season. Acma = maple, Acmi = yarrow, Alsi = Sitka alder, Anma = pearly everlasting, and Epan = fireweed.

reclamation, and may reduce replanting costs (Fedkenheuer et al. 1980). Pearly everlasting survivors had very little growth in the tailings, however it showed a strong positive response to the amendment of gravel over tailings exhibited through an increase in height growth.

The amendment of biosolids to G/T resulted in an increase in vertical growth for all five native plant species. Fireweed displayed a dramatic increase in vertical growth with the amendment of biosolids to G/T. While fireweed mean height growth in G/T (and T) was slightly negative, it's growth in B+G/T far surpassed that of all other species in this study (figure 2c). Fireweed's height growth was almost 3 times greater than Sitka alder, the species with the next greatest height growth. Height growth of Sitka alder and pearly everlasting increased by 50% and 100% respectively with the amendment of biosolids to G/T.

Biomass Production. Production of biomass (dry matter) is presented in Figure 3. As with height growth, Sitka alder also had the greatest biomass production of all species in the tailings surpassing that of the next species (pearly everlasting) over 8-fold. Very little biomass was produced by other species in the tailings; maple and yarrow survivors had slight losses of dry matter.

Interestingly, Sitka alder showed considerably less biomass production in G/T than in T. This may be due to differences in water-holding capacity. Sitka alder plants (and the other species as well) in G/T were primarily rooted in the gravelly sand layer above the tailings with little or no roots extending down into the tailings. Consequently, individual plants in G/T were not able to access available water in the tailings below. In the tailings treatment, Sitka alder was apparently more tolerant than the other species of the toxic edaphic environment. Sitka alder, therefore, was able to benefit from the presumed increased quantity of available water in the tailings (the silt and clay sized tailings undoubtedly had a higher water-holding capacity than the gravelly sand of G/T).



Figures 3a-c. Total biomass production (mean dry wt.) of five native plant species in tailings, gravel over tailings, and biosolids amended gravel over tailings. Acma = maple, Acmi = yarrow, Alsi = Sitka alder, Anma = pearly everlasting, Epan = fireweed. Species with same letter within the same treatment are not significantly different.

All other species displayed an increase in biomass production in G/T relative to T. This response may be due to a combination of reductions in acidity and Al toxicity, and an increase in available phosphorus. Pearly everlasting had 136% greater biomass production in G/T compared to T.

The amendment of biosolids to G/T elicited a positive response in biomass production from all species except big leaf maple. Reasons for the failure of maple to respond to the biosolids amendment are unclear. Production of dry matter in B+G/T increased by 62, 25, 7.6, and 2.4 times over that in G/T for fireweed, yarrow, pearly everlasting, and Sitka alder respectively. The growth of fireweed in B+G/T was decidedly superior to that of the other species (figure 3c). In general, the herbaceous species exhibited a much greater response to the biosolids than did the woody species. This may result from a greater physiological flexibility of herbaceous species (Bazzaz 1979). Because woody species must utilize energy in the production of wood, their growth response (at least in the short term) is prone to be more limited than herbaceous species (Grime and Hunt 1975).

While Sitka alder survival in B+G/T was twice that in the tailings, there were no differences in mean biomass production. There may have been moisture limitations which restrained the ability of Sitka alder to respond to the biosolids. In a greenhouse study, Kramer et al. (manuscript in preparation) demonstrated significantly higher biomass production of Sitka alder in B+G/T than in tailings alone.

The combined total biomass production of all species was 20g in T, 24g, in G/T, and 164g in B+G/T. This equates to 20% greater biomass production in G/T than T, and 580% more in B+G/T than G/T. The majority of this production of biomass in B+G/T was accounted for by fireweed.

Nutrient Uptake

Plant analysis indicated a dramatic increase in nutrient content with the biosolids amendment (Table 2). Of particular interest is the magnitude of differences in nutrient uptake between the Sitka alder in T and B+G/T where dry matter production was equivalent. Uptake of N, P, K, Ca by Sitka alder in B+G/T is higher than in T by 25, 550, 175, and 510 percent respectively. Because biomass production was no different than in tailings alone, this increase in macronutrient uptake in B+G/T lends support to the previous assertion that a moisture limitation may have restricted the growth response of Sitka alder to the amendment of biosolids.

A clear trend of increasing nutrient uptake with increasing biomass production was shown by pearly everlasting progressing from T to G/T to B+G/T. Although pearly everlasting had a small amount of growth in the tailings, there was no uptake of P. Growth was supported by a dilution of P initially present in the plants. This species was not able to access phosphorus from the tailings. The amendment of biosolids to G/T increased nutrient uptake by pearly everlasting by an order of magnitude

Table 2. Total uptake of selected nutrients and metals by four native plant species in copper mine tailings (T), 15 cm gravel over tailings (G/T), and biosolids amended gravel over tailings (B+G/T).

	biomass	N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	Al
Sitka alder	g	µmol										
T	2.1	2800	12	160	82	130	83	200	5	2.7	1.4	130
G/T	0.9	1300	15	110	150	58	26	46	8	1.1	0.3	56
B+G/T	2.1	3500	80	440	500	140	110	140	15	12	1.3	98
Pearly everlasting												
T	0.25	34	0	36	13	10	8	19	0.2	1.8	0.08	7
G/T	0.6	540	46	300	86	39	22	24	2	1.6	0.4	22
B+G/T	4.4	7850	360	3080	850	330	270	180	11	19	2.0	97
Yarrow												
B+G/T	1.3	3200	87	1070	290	130	95	79	6	7.5	0.88	46
Fireweed												
B+G/T	11	26000	1050	4100	3100	780	450	56	18	39	2.2	32

over that in G/T. The increased growth of pearly everlasting (from T to G/T to B+G/T) may be related to total soil nitrogen (Kramer et al. manuscript in preparation).

The large amount of biomass produced by fireweed in B+G/T relative to the other species is reflected in nutrient uptake as well. This species shows a much higher level of nutrient acquisition and growth in this treatment than any species in any treatment. Fireweed uptake of N, P, K, and Ca in B+G/T exceeded that of pearly everlasting by 225, 190, 35, 260 % respectively. Fireweed has the ability to quickly colonize a disturbed area (e.g. by fire, clearcutting, etc.) through wind dispersal of its minute, light-weight seeds (Strand 1957, Halpern 1989). Fireweed populations then rapidly expand through vegetative reproduction via rhizomes. Based on the nutrient uptake data in this study, it would appear that this species is performing a critical ecological function of nutrient conservation during the initial stages of ecosystem recovery. Fireweed utilized in combination with an amendment of biosolids may be an effective method of initiating the processes of carbon sequestration and nutrient cycling in the ecological restoration of copper mine tailings.

However, one must consider the potential for competition from this species in slowing the establishment of a forest community (Simard and Nicholson 1990). While the long-term ecological consequences (re. impact on the rate of succession) of making nutrient additions and encouraging colonization by early successional species is unclear (Zabowski et al. 1993), some have reported short-term dominance of fireweed in successional patterns following disturbance usually leading into a shrub-dominated phase (Franklin and Dyrness 1988). Other studies have reported long-term persistence of this species (Halpern 1989), so caution is to be exercised if rapid reforestation is desired. Long-term study of the successional pathways following biosolids application and establishment of fast-growing species with the predisposition for high rates of nutrient uptake (e.g. fireweed) would prove useful.

Conclusions

Biosolids improved the survival, growth, and nutritional status of native plant species on the copper mine tailings at Holden, WA. Organic matter and total nitrogen increased more than 40 times that of G/T following the application of biosolids to G/T. Available phosphorus was almost doubled. Exchangeable Ca, K, Mg and cation exchange capacity tripled with the amendment of biosolids to G/T. Mean plant survival of all 5 species increased from 42 to 72 to 90% in T, G/T, and B+G/T respectively. Biomass production (dry wt.) in B+G/T increased by 62, 25, 7.6, and 2.4 times over that in G/T for fireweed, yarrow, pearly everlasting, and Sitka alder respectively.

Phosphorus deficiency/aluminum toxicity associated with high levels of acidity are suspected as critical growth-limiting factors in the tailings. Deficiency of nitrogen in the tailings is also evident. In addition, there appear to be areas where iron toxicity may be a severe problem. Sitka alder demonstrated a remarkable degree of tolerance to the tailings; growth of other species was seriously impaired.

Fireweed demonstrated exceptional performance in the biosolids-amended gravel over tailings. The growth and nutrient uptake of fireweed far exceeded that of other species in B+G/T. Fireweed utilized in combination with an amendment of biosolids may be an effective method of initiating the processes of carbon sequestration and nutrient cycling for the long-term ecological restoration of copper mine tailings. Overall, biosolids improved the survival, growth, and nutritional status of native plant species tested on the copper mine tailings.

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