USING MUNICIPAL BIOSOLIDS IN COMBINATION WITH OTHER RESIDUALS TO RESTORE METAL-CONTAMINATED MINING AREAS

by

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Abstract. High metal waste materials from historic mining in both upland and wetland environments at the Bunker Hill, ID and Leadville, CO Superfund sites were amended with a mixture of biosolids and lime or high CCE (calcium carbonate equivalent) materials. For all sites, the existing soils have elevated metal concentrations with total Zn, Pb and Cd ranging from 6,000 – 14,700, 2100 – 27,000, and 9 – 28 mg kg^{-1}, respectively. Application of the biosolids mixture at each site resulted in significant decreases in subsoil acidity as well as subsoil extractable metals. In a series of small-scale uplands field plots at both the Bunker Hill and Leadville sites, this mixture was sufficient to restore a vigorous plant cover to the contaminated areas. In addition, application of a residuals mixture was sufficient to restore a plant cover to a wetland that had been used as a tailings repository in Bunker Hill. At the Bunker Hill site, surface application of biosolids (112 Mg ha^{-1}) in combination with wood ash (220 Mg ha^{-1}) and logyard debris (20 % by volume) was able to restore a vegetative cover to the metal contaminated materials for three years following amendment application. Plant biomass in 1999 was 0.01 Mg ha^{-1} in the control versus 3.4 Mg ha^{-1} in amended plots. Metal concentrations of the vegetation indicate that plants were within normal concentrations for the 3 years that data was collected. Surface application of amendments was also able to reduce $Ca(NO_3)_2$ extractable Zn in the subsoil from 159 mg kg^{-1} in the control to 10 mg kg^{-1}. In the wetland site at Bunker Hill, surface application of a biosolids compost (60% dry weight) and wood ash (40% dry weight) to a depth of 15 cm was sufficient to enable a volunteer plant community to reestablish in the treated area. Metal concentrations in reeds in the amended area were within normal range. In Leadville, both the surface and subsoil pH of the high pyrite tailings materials were increased with a biosolids (180 Mg ha^{-1}) and lime (224 Mg ha^{-1}) mixture. While concentrations of Zn in annual ryegrass were above normal levels, there was no indication of toxicity. These results indicate that surface application of biosolids in combination with other residuals are sufficient to restore a vegetative cover to high metal-containing soils under a range of soil and climactic conditions.

Additional Key Words: organic residuals, biosolids, contaminated mine sites, vegetation establishment

Introduction

Biosolids have been used both alone and in combination with other materials to restore soils that have been disturbed by a wide range of activities including coal and gravel mining. The use of biosolids is a long-standing practice with many sites having been successfully restored for 25 years or more (Sopper, 1993). Research has consistently demonstrated that biosolids are highly effective, in many cases more so than topsoil replacement, for restoration of disturbed ecosystems. Biosolids, applied at restoration rates (generally greater than 112 Mg ha^{-1}) provide sufficient organic matter to improve soil physical properties. Water infiltration as well as water holding

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capacity is increased. Bulk density of disturbed soil is also generally decreased. In addition, biosolids provide all of the micro and macronutrients necessary for plant growth. The high organic fraction of biosolids serves as a food source for soil microorganisms. The presence of a large microbial population insures that the nutrients in the biosolids will be recycled and available for subsequent growing seasons. A single application of biosolids has been able to sustain a vigorous vegetative cover for several decades at a range of sites. For conventional soil restoration practices, biosolids appear to be the most effective method that is currently available. As acceptance of this restoration technology has increased, modifications in amendment mixtures have also grown to be more common. Amendment mixtures are often created to achieve specific soil chemical objectives (Brown et al., 2000). It is possible to use combinations of materials to correct specific problems in the affected ecosystem. Biosolids have been mixed with high CCE residuals to restore acid coal mine wastes. Where concerns over excess nitrates exist, biosolids have been combined with high carbon materials, to reduce the potential for nitrate leaching.

In recent years, there has been a growing recognition that biosolids may also be used to restore metal-affected ecosystems. Initial concerns about potential negative effects to plant and human health as a consequence of application of high metal biosolids to agricultural lands prompted a great deal of research on the behavior of metals in biosolids amended soils. Scientists have consistently demonstrated that metals in biosolids are much less available than equivalent metals added to soils as salts (Brown et al, 1998). In addition, use of high quality biosolids generally results in no observable increase in plant metals (Brown et al, 1998). It should be noted that many of the historical biosolids restoration projects used material that would not be acceptable for beneficial use under current regulations (Haering et al., 1998) . Metal concentrations in these biosolids were significantly higher than is currently allowed under CFR Part 503. In fact, the metals in historic biosolids used were as high as soil metal concentrations in some of the mining affected sites that are on US EPA Superfund's NPL. Despite this fact, the sites that were restored using these materials have been able to maintain healthy plant cover with plant metal concentrations within an acceptable range (Sopper, 1993). From these observations as well as research on the phytoavailability of metals in biosolids/soil systems came the notion that high quality biosolids could be used to limit metal toxicity in metal contaminated soils. As a quantitative understanding of the metal binding properties of biosolids is developed, it may be possible to tailor biosolids application rates to correspond with metal concentration in the affected soil (Li et al., 2000).

At the present time, for use on metal contaminated sites, biosolids must be combined with either conventional limestone or high CCE residuals to be fully effective for restoration. Research at Palmerton, PA and Katowice, Poland demonstrated that application of biosolids in combination with high calcium carbonate equivalent residuals to highly metal contaminated soils was sufficient to restore a vegetative cover (Sopper, 1993, Stuczynski et al., 1997). The current research was undertaken to determine if a similar remediation mixture would be effective at restoring a self-sustaining vegetative cover at the Bunker Hill and Leadville Superfund sites. Use of this technology offers an alternative to current accepted technologies within the Superfund program.

Bunker Hill, ID and Leadville, CO are both included on US EPA Superfund's Nation Priorities List. Mining and smelting of Zn and Pb ores for much of the 20th century has resulted in extensive metal contamination of the surrounding hillsides and waterways for both sites. Research was conducted by the University of Washington in cooperation with the USDA-ARS and US-EPA-ERT to test the ability of a range of soil amendments to assist in the establishment of a vegetative cover on the contaminated materials in each of these areas under a range of soil moisture regimes.

Bunker Hill

At Bunker Hill, ID, the area that falls under the Superfund designation is well over 600 ha. As part of their clean-up efforts, EPA has been depositing contaminated tailings and dredged materials in a Central Impoundment Area (CIA). These materials generally contain high concentrations of potentially phytotoxic metals, little to no organic matter, are moderately to severely acidic, and are deficient in necessary macro and micro-nutrients. In addition, during the period when active mining took place, over 70 million Mg of mine tailings were deliberately deposited into the Coeur D'Alene River system with accidental deposits to the River potentially as high as 10 times that amount (Earl Liverman, US EPA Region 10, personal communication). The West Page Swamp, located within the designated site was used as a tailings repository from 1920 - 1927. Tailings in the swamp comprise at least the upper 3 m of soil material.

Applications. At Bunker Hill, field plots were installed in June of 1997 and consisted of large-scale treatment plots (33 x 33 m) in a completely randomized design with 3 replicates. A second series of plots (1 x 4 m) was established in October, 1997. The surface soils in this area consist of mining waste material with little to no organic matter. These materials contain 5500 -14,700 mg kg^{-1} Zn , 1500 to 4900 mg kg^{-1} Pb, and 7 to 28 mg kg^{-1} Cd. Soil pH ranged from 4.6 to 7.0. Amendments for this study included high N (4.4-5.3%) and low N (2.8%) biosolids applied at 55 and 110 Mg ha^{-1} dry weight. The high N biosolids were produced through anaerobic digestion. The low N biosolids were stabilized in a lagoon. While all of the biosolids used met US EPA CFR Part 503 requirements for Class B pathogen reduction, the lower N biosolids were much more stable. Longer retention time in the treatment lagoon is associated with greater decomposition of organic matter and a more stable end product. A list of treatments used in the first phase of the Bunker Hill study, with their associated characteristics, is presented in Table 1.

For the Phase I study, biosolids were mixed with 220 wet Mg ha^{-1} wood ash (to provide the calcium carbonate equivalent of 55 Mg ha^{-1}) before application. Logyard waste (20% by volume) was mixed with the low N biosolids treatments and two of the high N treatments to reduce the potential for nutrient runoff by increasing the C:N ratio of the amendments. A single high N biosolids treatment (N3) was applied without logyard waste at the high application rate (110 Mg ha^{-1}). All amendments were mixed with a front-end loader immediately prior to application. Materials were surface applied using a side cast thrower that was mounted on a 6-wheel drive vehicle. The throw distance of the mixture was approximately 60 m. There was no attempt made to incorporate the amendments. A control treatment was also included. Phase II consisted of a second series of plots that tested a wider range of amendments, including primary pulp and paper sludge and biosolids compost. Conventional restoration amendments and proposed treatments by venders (such as 'Kiwi Power') were also included in the study (Table 2).

Table 1. Characteristics of the amendments used in the Phase I portion of the Bunker Hill study (values are the mean of 3 replicates, ± std dev).

	Zn	Cd	Pb	pH	Carbon	Nitrogen	Solids	Depth
	- - - - - - mg/kg - - - -				- - - - - - - - % - - - - - - - -			(cm)
Low N								
56 Mg ha	1800±400	6.1±0.7	270±100	8.4±0.4	17±2	0.5±0.1	60±5	4.1±2.5
112 Mg ha	1100±200	9.0±0.6	220±20	7.6±0.1	20±2	1.1±0.2	49±7	6.1±2.3
High N								
56 Mg ha	1200±400	2.7±0.1	100±20	8.7±0.2	19±3	1.0±0.2	45±3	4.6±1.8
112Mg ha	900±100	2.7±0.1	230±30	8.5±0.1	21±4	1.8±0.6	37±3	8.1±2.3
High N (- log yard)								
112 Mg ha	550±20	2.6±0.1	170±30	8.4±0.1	24±1	2.2±0.3	30±4	5.8±1.8

Seeding. Seeds were hand-scattered on the surface of the amendments immediately prior to application. A native seed mixture that had been used elsewhere on the site was used as the initial seed mix. Although this type of seeding technique had been successfully used at Palmerton, PA, the high pH of the wood ash (pH> 11) in combination with the high N content of the biosolids resulted in sufficient ammonia volatilization to kill of the seeds in the high N biosolids treatments. Subsequent reseeding as well as volunteer species were sufficient to establish a vegetative cover later in the first growing season. Additional studies at the site suggest that a waiting period of 48 hours is sufficient to avoid seed germination failure due to excess ammonia. Use of a less caustic lime product would also reduce the rate of ammonia volatilization.

Table 2. Material loading rates for treatments used in Phase II plots of the University of Washington field study on the use of residuals to restore a vegetative cover on the CIA.

Treatments	Biosolids	Ash	Logyard	Pulp fines	N

	- - - - - - - - - - dry Mg ha^{-1} - - - - - - - - - -				kg ha^{-1}
Low N (L-N-L+Ly)	66	155	55		
Low N (L-N-L)	66	155			
Low N (L-N-H)	99	155			
Low N (L-N-H+Ly)	99	155	55		
High N (H-N-L+Ly)	44	155	55		
High N (H-N-L)	44	155			
High N (H-N-H)	66	155			
High N (H-N-H+Ly)	66	155	55		
High N (H-N-L+KC)	44	175			
High N (H-N-H+P-A)	66			44	
High N (H-N-H+P)	66	155		44	
High N2 (H-N2+Ly)	66	155	55		
Biosolids Compost (Comp)	165	155			
Logyard waste (Ly+N)	110	155			200
High N3 (H-N3+Ly)	50	155	55		
Soil only (Ctrl)					
Bitterroot Biosol (Biosol)					
Bitterroot KiwiPower (Kiwi)					
Glacier Gold (GGold)					

Notes: "L-N-L+Ly" stands for Low N biosolids at Low rate with Logyard waste. "H" stands for high. There are 3 different high N biosolids (H-N, H-N2, H-N3). "P" stands for pulp fines, "KC" is a different kind of wood ash than the other treatments, "-A" means no ash was added.

Sampling. Plant samples for elemental analysis were collected in August, 1997(Phase I), July, 1998 (Phase I and II) and June, 1999 (Phase I and II). In each case, a composite sample, consisting of a minimum of three subsamples, was collected from each plot for elemental analysis. For this purpose, only grass samples were collected. The samples were washed and rinsed in deionized or distilled water. Samples were ashed at 480 C°, digested with concentrated HNO_3, and analyzed using a flame atomic adsorption spectrometer or an inductively coupled plasma spectrometer. Values were corrected for background variation through the use of blanks, and the inclusion of replicate samples. NIST plant standards were routinely included in the digests. Percent cover was measured in 1998 using the line transect method. Three measures, each 17 m in length were taken on each plot. Occurrence of plants within each 20 cm increment was interpreted as being vegetated. Harvestable biomass was measured in 1998 (Phase II) and 1999 (Phase I and II). Samples for biomass measurements were collected from 3 areas of each plot using a circular measure that was 615 cm^2. All plants within the circular measure were included in the biomass measurements.

In addition to plant samples, soil samples were collected in the 0-15 cm horizon directly below the amendment in 1999. These samples were analyzed for pH and extractable metals using a 0.01 M $Ca(NO_3)_2$ extraction. Samples from the amended horizon were collected in all years and analyzed for carbon and nitrogen concentrations. It has been suggested that the C:N ratio of the soil over time will give an indication of the amount of microbial decomposition and therefore nutrient cycling in a soil system (Steve McGrath, IACR, Rothamstead, UK, personnel communication).

Results and Discussion

Soils. Soils were analyzed for $Ca(NO_3)_2$ extractable metals. This extraction was designed to mimic the soil solution. In cases of contaminated soils, soil solution metals have been well correlated with plant available metals. Results from extractions from Phase I are presented in Table 3, while Figure 1 shows extractable zinc in soil below Phase II treatments.

Table 3. Soil pH and extractable (0.01 M $Ca(NO_3)_2$) Zn of the amendments and subsoil in the Phase I plots in 1999.

Treatment (mg kg^{-1})	pH	Extractable Zinc
Control	5.8±0.9	150±60
Low N 110		
amendment	7.1±0.5	1.9±0.3
soil	5.9±1.0	87±60
Low N 55		
amendment	7.8±0.1	0.8±0.1
soil	7.3±0.4	11±1
High N3 110		
amendment	7.4±0.1	1.0±0.1
soil	7.6±0.2	12±2
High N 110		
amendment	7.3±0.3	1.0±0.1
soil	7.0±0.6	14±6
High N 55		
amendment	7.8±0.2	1.7±0.6
soil	7.5±0.5	9±2

The reduction in $Ca(NO_3)_2$ extractable Zn along with increased soil pH that was observed in the subsoil under several treatments suggests that the alkalinity added with the surface amendment was partially mobile in the soil solution. Reduced concentrations of Zn in the soil solution indicate a reduction in phytotoxicity. The proliferation of roots into the subsoil in the Phase I and Phase II plots (visual observation) may be a result of the amendment's ability to reduce bioavailable metal concentrations in the subsoil. These results also suggest that the higher N biosolids which are less stable and decompose more readily than the low N biosolids, are more effective at translocating alkalinity to the untreated subsoil. Increased subsoil pH and extractable Zn concentrations in the high rate of the low N biosolids treatment in Phase I indicates that this treatment was less effective at reducing subsoil phytotoxicity and would also be less successful at maintaining a stable plant cover for an extended period. The reason for the lower subsoil extractable Zn and higher pH in the lower application rate of this treatment is not clear. Addition of logyard waste appeared to have no effect on subsoil pH concentrations or extractable metal concentrations. In the Phase II plots, the subsoil extractable Zn was significantly lower than control and conventional treatments in the range of residuals treatments that included wood ash and biosolids or biosolids compost. There was also a significant increase in plant biomass over control and conventional treatments. As in the Phase I portion of the study, the low N biosolids did not perform as well as the high N, more reactive materials.

Changes in the C:N ratio of the amendment horizon over the three year period of the study are presented in Figure 2. A stable C:N ratio of approximately 20:1 is indicative of a well functioning soil system. The initial amendment, at the high rate of application of the high N biosolids, had C:N ratios of under 12:1. This indicates a surplus of N in the system. As plants grow on the soil and plant tissue is deposited on the soil surface, the C:N ratio will increase. A ratio significantly over 25:1 indicates that there is not a sufficiently active soil community to decompose plant residues. If this is the case, the nutrients that have accumulated in plant tissue will not be recycled in the soil system and so will not be available for future growing seasons. The C:N ratios in Figure 2 indicate that this ratio is within the healthy range for all of the high application rate of the low and high N biosolids treatments. For the low rate of both types of biosolids, the ratio either appears to be increasing (high N treatment) or remaining relatively high (low N treatment). This may suggest that there is not sufficient nutrient cycling in these systems to maintain a self-sustaining vegetative cover. The addition of logyard waste did not appear to change the nutrient cycling dynamics in the high N biosolids treatment.

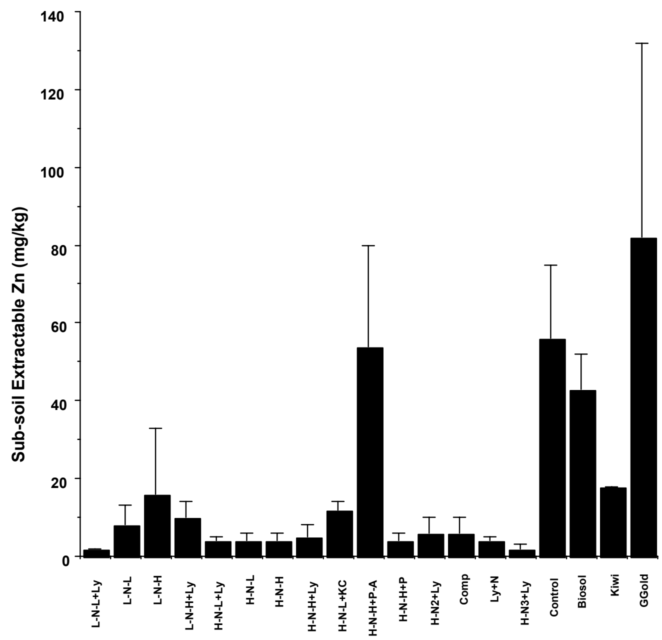

Figure 1. $Ca(NO_3)_2$ extractable zinc in soil below Phase II treatments.

Plants - Diversity and rooting patterns. The native mix that had been used on the hillside revegetation study was also used for the initial seeding of the Phase I plots. Germination of a wide range of grasses and legumes was observed on the low N biosolids treatments. The ammonia toxicity on the high N treatments killed all seedings. Volunteer species began colonizing these plots before they were reseeded. These species included crab grass and bunch grasses. Subsequent reseeding of these plots was done using a wheat grass and vetch mixture. Random plants were pulled from several treatments during each sampling period. Roots for all plants pulled had penetrated the subsoil below the amendment. Root growth into the subsoil was extensive. Low concentrations of extractable Zn may have enabled root growth into the subsoil. In addition, legumes checked showed effective nodulation. Root nodules were cut open and were bright pink, indicating that rhizobia were actively fixing N.

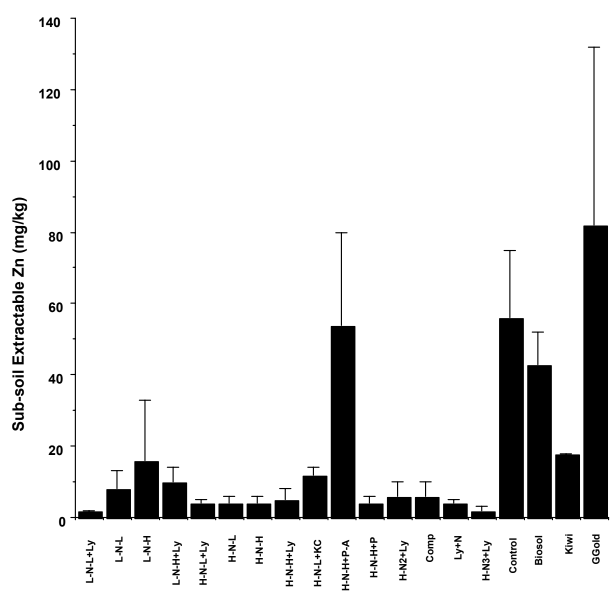

Figure 2. Changes in the C:N ratio of the amendment horizon over the three year period of the Phase I study on above ground mine tailings in Bunker Hill ID.

Plants - Biomass. Percent cover and harvestable biomass for the Phase I plots are presented in Table 4, and dry biomass produced in Phase II is shown in Figure 3. In Phase I the highest biomass was found in the high application rate of the low N biosolids as well as all rates of the high N biosolids. The absence of logyard waste in the amendment mix appeared to have no effect on plant cover. The high concentrations of soluble Zn in the subsoil of the high rate of the low N biosolids did not appear to have any impact on biomass. It is possible that there was sufficient moisture in the early part of the growing season (measurements were made in June, 1999) so that plants did not need to access moisture in the subsoil. In cases of limited rainfall, high Zn concentrations in the subsoil would effectively prohibit root growth into this horizon and would thereby limit access to soil water. In Phase II all the high N treatments had good biomass production, the low N treatments had moderate production, while the control, conventional and special treatments had very low biomass produced.

Table 4. Percent cover on Phase I plots in July, 1998 and harvestable biomass in June, 1999. Reported values are the means of 3 replicates (± std dev).

Treatment	Rate ($Mg\ ha^{-1}$)	% Cover	Harvestable biomass ($Mg\ ha^{-1}$)
Control		0%	0±0
Biosolids			
Low N	55	77%	1.6±1.0
	110	93%	2.5±1.6
High N	55	82%	4.0±1.3
	110	93%	2.8±1.3
High N -			
Logyard	110	95%	3.0±1.3

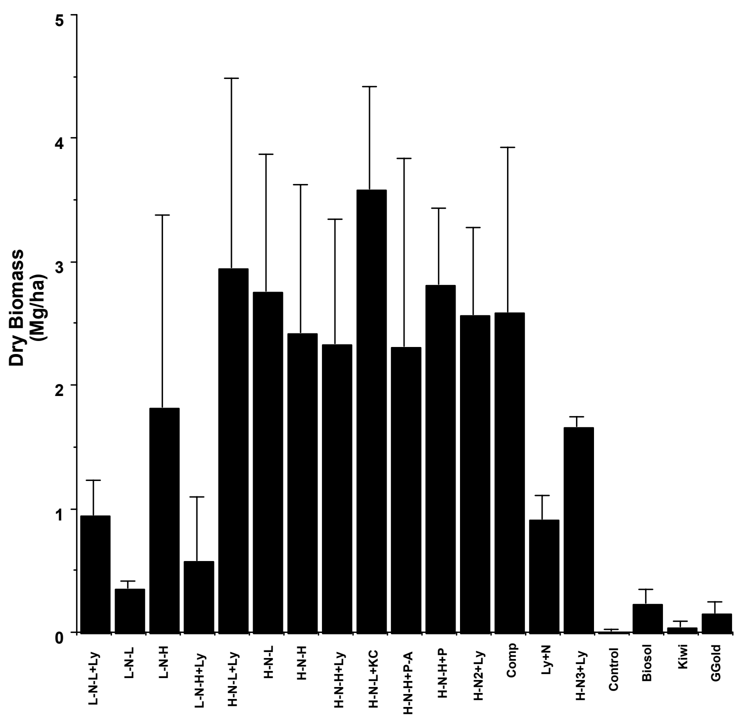

Figure 3. Dry biomass produced by late July 1998 by Phase II plots.

Plant metal and nutrient status. Plant metals were measured on the Phase I plots in 1997, 1998 and 1999. Results of these analyses are presented in Table 5. There was no vegetation on the control plots in 1998. The decrease in plant Zn, Cd, and Pb from 1997 to 1998 is not unusual. Metals in biosolids amended soil are generally more phytoavailable during the first growing season following application (Brown et al., 1998). Results from this study are consistent with results of studies using biosolids on agricultural soils. Concentrations of Zn in the biosolids amended soils are similar to those expected for plants grown on uncontaminated soils. The increase in plant Zn from 1998 to 1999 is potentially the result of seasonal variation. Additional monitoring would be necessary to confirm this observation. In all years when there was harvestable plant tissue on the control plots, plant analysis indicated severe P deficiency. This type of deficiency is relatively common for plants growing on high Zn and Pb soils. P tends to form insoluble complexes with these metals and is generally limiting for plant growth. Phosphorus concentrations in the amended treatments were all within normal ranges, however, there was a decrease in plant P in the 1999 growing season. All of the amendments contained excess P for plant growth. This decrease may indicate that the excess P has formed insoluble precipitates and is no longer available to plants. After the first growing season, plant concentrations of Zn and Pb were significantly lower in the amended as compared to control treatments. Cadmium concentrations for all treatments are similar for all years. Copper concentrations are comparable in all treatments across all years with the exception of the low rate of the high N biosolids + log yard waste in 1999. In this treatment, plant Cu concentrations are approaching deficiency. There was a significant amount of copper added with the biosolids and wood ash amendment and this deficiency may be the result of high soil pH and the dissolution of organo-Cu complexes that had kept Cu solubility high in the initial years of the study.

Table 5. Elemental concentrations of plant tissue grown on Phase I plots in Bunker Hill, ID for 3 years following amendment application (± std dev).

App. Rate		Plant Cd	Plant Cu	Plant P	Plant Pb	Plant Zn
		- - - - - - - - - - - -	- - - - - - - -	($mg\ kg^{-1}$)	- - - - - - - -	- - - - - - - - - - - -
1997						
Normal Plant		0.1-1.5	5.0-15	>1500	0.1-6	20-400
Control		0.4 ± 0.1	3.9 ± 0.9	900 ± 200	8.5 ± 2	219 ± 20
Low N	55	1.4 ± 0.3	12 ± 1	3900 ± 400	11.8 ± 2	105 ± 20
	110	2.3 ± 0.6	11.4 ± 0.3	2400 ± 1000	15.4 ± 5	152 ± 20
High N	55	1.2 ± 0.2	16 ± 2	4500 ± 400	16.2 ± 0.5	129 ± 1
	110	0.6 ± 0.3	10 ± 3	7400 ± 3000	6.7 ± 0.6	114 ± 25
High N3	110	0.9 ± 0.7	14 ± 1	7000 ± 400	8.4 ± 0.7	70 ± 6
1998						
Low N	55	0.7 ± 0.1	4 ± 1.0	3100 ± 400	2.3 ± 0.6	38 ± 5
	110	1.7 ± 1.2	5.8 ± 0.3	3200 ± 20	2.7 ± 0.4	61 ± 13
High N	55	0.9 ± 0.1	5.1 ± 0.5	3800 ± 400	2.7 ± 1.0	47 ± 7
	110	0.9 ± 0.2	9 ± 3	5100 ± 600	3.0 ± 0.7	59 ± 12
High N3	110	0.8 ± 0.3	6 ± 2	3800 ± 200	2.8 ± 1.2	48 ± 7
1999						
Control		0.50 ± 0.06	5 ± 0.5	700 ± 100	27 ± 9	169 ± 10
Low N	55	0.5 ± 0.1	5 ± 0	1790 ± 60	3.5 ± 0.8	63 ± 3
	110	0.6 ± 0.4	5 ± 0.5	1800 ± 100	2.6 ± 0.9	94 ± 10
High N	55	0.28 ± 0.04	3.0 ± 0.5	1700 ± 200	3.0 ± 0.4	47 ± 10
	110	0.40 ± 0.08	5 ± 0.5	2100 ± 300	4.0 ± 1.0	85 ± 4
High N3	110	0.6 ± 0.1	6.0 ± 2	2500 ± 800	4.8 ± 0.8	89 ± 10

West Page Swamp, ID

A mixture of biosolids compost and wood ash (3:1 by volume) were surface applied to the West Page Swamp in October, 1998. The swamp is located west of and adjacent to the Bunker Hill site. It had been used as a tailings repository for a mill during the 1920s. The existing soil material in the swamp consisted of tailings to a measured depth of at least 3 m. Metal concentrations of this material were up to 30 g kg^{-1} Pb and 15 g kg^{-1} Zn. As part of a closure agreement with EPA Region 10, the mining companies involved in the site had excavated surface soil material from a section of the pond. Applications were made using an AeroSpread from both the adjoining county road and from a road built through the center of the swamp using log yard debris. The amendment was surface applied through standing water in the wetland. The compost mixture settled within 3 days after application. At the end of operations, the logyard road was eradicated, leaving an irregular surface to resemble the undulations of a naturally occurring wetland. Water samples have been collected at the outflow point of the wetland both prior to and after amendment application. Nutrient concentrations in the water have been within acceptable levels throughout this period. Cattails and Sagittarius were hand planted in 3 areas in June 1999. In September of 1999, volunteer vegetation had colonized a large portion of the wetland. There was extensive evidence of fish and avian life in the restored area. Depth measurements of the amendment across several transects indicated that the compost mixture was unequally applied over the bottom surface; an artifact of the application equipment . There was no evidence that any material had moved out of the swamp area (hay bales and a silt fence at the end of the pond hadn't collected any particulate matter). However, over the winter, heavy wave action eroded some of the compost mixture from the shore. Amending the wetland earlier in the growing season, with subsequent plant establishment, would reduce the potential for amendment erosion on the banks.

Plant samples were collected before amendment application in both the excavated portion of the Swamp as well as in a neighboring vegetated section. Samples were also collected from the planted areas the following year. Analyses of these plants are presented in Table 6. Although reeds had been planted in a control (unamended) section, there were no surviving plants when samples were collected. Analysis of the plant tissue indicates that amendment application was able to reduce Zn concentrations to below phytotoxic levels. A pot study was also conducted with tailings collected from the West Page Swamp. Under controlled conditions with a consistent depth of amendment as well as a controlled water level, amendment application was able to reduce plant extractable metals to within normal concentrations. In addition, analysis of the tailings material from the pots that received the compost wood ash amendment, suggests a change in mineral form of the Pb from a combination of Pb oxide and PbS (galena) to galena (Dean Hesterberg, North Carolina State University). This suggests that, with more controlled amendment application to a consistent depth and with consistent anaerobic conditions, it may be possible to limit metal toxicity and restore a vegetative cover under anaerobic as well as aerobic soil conditions.

Table 6. Zinc, Pb and P concentration of cattail (*Typha latifolia*) collected from the West Page Swamp in Bunker Hill, ID both prior to and post amendment with biosolids compost and wood ash.

	Plant Zn	Plant Pb	Plant P
	- - - - - - - - - - - - $\mu g\ g^{-1}$ - - - - - - - - - - - -		
1998			
Control	1010	125	814
Vegetated area	57	10.1	1547
1999			
Control			
Treated area	173	3.59	3866

Leadville, CO

In Leadville, high pyrite wastes from mine tailings piles entered the Arkansas River during storm events. Deposition of these materials has contaminated areas along an 11-mile stretch of the river (Jan Christner, URS Greiner, Denver CO, personal communication). The fluctuating water table has resulted in alternating reducing and oxidizing conditions. Oxidation of the reduced sulfur has resulted in extremely acidic soil pH (1.5-4.5). As a function of the fluctuating water table and the acidic conditions, Zn and Pb form soluble salts and wick to the soil surface during dry portions of the year. A metal salt crust forms on the soil surface with measured Zn concentrations of up to 90 g kg^{-1}.

A field experiment was installed in September, 1998 to determine if biosolids in combination with limestone could restore a vegetative cover to the tailings deposit. A randomized complete block design was used for the trial. Two rates of biosolids (90 and 180 Mg ha^{-1}) as well as 2 types of biosolids (cake at 18% solids from Denver Metro and pellets at 98% solids from Boston) were used for the study. Lime was added at 224 Mg ha^{-1}. Lime alone biosolids alone treatments were also included in the study. Material was incorporated into the top 12 cm of the soil using a rototiller. Plots were seeded with annual rye grass in July, 1999. Plant and soil samples were collected in September, 1999. Plant samples were analyzed as previously described. Soil samples were analyzed for $Ca(NO_3)_2$ extractable metals as well as pH.

Treatments increased pH and decreased extractable metals at least in the surface horizons, as shown in Table 7. We expect this to continue as the Ca and Mg from the lime moves down through the soil profile. Also, initial results suggest that both types of biosolids, in combination with lime, were highly effective at restoring a plant cover on the amended areas. Table 8 presents plant metal concentrations for annual rye grass grown on the plots.

Table 7. Soil pH and $Ca(NO_3)_2$ extractable metals (± st dev) in biosolids and lime amended plots in Leadville, CO 1 year after amendment application. Total Zn ranged from 3400 to 3900 mg kg, total Pb ranged from 2100 to 4100 and total Cd ranged from across the 0 – 45 cm depths.

Treatment	Depth (cm)	pH (units)	Cd	Pb	Zn
			- - - - - - ($mg\ kg^{-1}$) - - - - - -		
Control					
	0-15	3.9 ±0.8	11 ±8	11 ±3	1200 ±700
	15-30	4.2 ±0.7	6 ±2	18 ±13	700 ±200
	30-45	4.9 ±0.5	5 ±7	3 ±3	600 ±400
Lime					
(224 Mg ha^{-1})	0-15	6.3 ±0.2	1 ±1	1.8 ±0.8	70 ±100
	15-30	4.4 ±0.4	5 ±2	15 ±8	600 ±300
	30-45	4.9 ±0.7	5 ±1	4.3 ±0.9	500 ±200
Biosolids only					
(180 Mg ha^{-1})	0-15	4.9 ±0.2	3 ±2	14 ±14	400 ±200
	15-30	4.8 ±0.7	6 ±2	11 ±5	600 ±200
	30-45	5.1 ±0.6	5 ±5	5 ±3	500 ±300
Wet biosolids + lime					
(180 Mg ha^{-1})	0-15	6.4 ±0.3	0.5 ±0.4	3 ±2	30 ±30
	15-30	5.7 ±0.5	2 ±2	2 ±1	200 ±200
	30-45	4.7 ±0.3	6 ±1	6 ±3	580 ±60
Dry biosolids + lime					
(180 Mg ha^{-1})	0-15	6.8 ±0.3	0.6 ±0.1	4 ±3	10 ±7
	15-30	5.1 ±0.6	3 ±2	5 ±3	400 ±200
	30-45	4.8 ±0.5	5 ±1	5 ±3	580 ±70

Table 8. Plant metal concentrations for annual rye grass grown on treatment plots in Leadville, CO one year after amendment addition. Values are the mean of 3 replicates. There were no plants in the control plots.

Treatment	Cd	P	Pb	Zn
Lime (224 Mg ha^{-1})	5.6	1900	67	700
Biosolids only (180 Mg ha^{-1})	2.2	6500	37	440
Wet biosolids (180 Mg ha^{-1}) + lime	2.6	4900	33	420
Dry biosolids 180 Mg ha^{-1}) + lime	2.2	6500	37	440

Conclusions

At all three of the sites reported, biosolids treatments were effective in establishing a vigorous plant cover. It appears that biosolids in combination with other materials can successfully be used to restore metal-affected ecosystems. It is also apparent that not all types of amendments are equally effective. The low rate of the low N biosolids used at Bunker Hill, ID did not achieve complete plant coverage of the plot area, indicating that the higher rate of amendment would be superior for plant growth. High extractable Zn concentrations in the subsoil of the high rate of the low N biosolids also suggest that the use of the high N materials (more chemically reactive) is a superior remedial alternative to the low N materials. The decreasing P concentrations in plant tissue over time suggests that rates higher than 112 Mg ha^{-1} may be required to sustain a plant cover. In the West Page Swamp, bank erosion of materials from wave action suggests that timing of application is very important. In addition, it may be necessary to seed areas to insure that a plant cover is established as quickly as possible. While initial results at Leadville are also promising, the failure of the limestone added to increase soil pH to >7.0 suggests that it may be more appropriate to use a more reactive liming material such as cement kiln dust. This would also help to reduce plant Zn concentrations. Despite these particular concerns, biosolids in combination with other materials appear to offer a viable alternative for restoration of metal-affected ecosystem. Additional research should enable scientists to more specifically determine appropriate amendment mixtures to address the specific characteristics of each site.

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