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FINAL REPORT

THE DEVELOPMENT OF SYNTHETIC SOIL MATERIALS FOR THE SUCCESSFUL RECLAMATION OF ABANDONED MINED LAND SITES

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By
Song Jin

And
State of Montana
Department of Environmental Quality
Helena, Montana

For
U.S. Department of Energy
National Energy Technology Laboratory
Morgantown, West Virginia

By
Western Research Institute
Laramie, Wyoming

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ABSTRACT

Abandoned mine sites associated with coal and metal mining across the western United States have been left as unproductive wastelands. The availability of soil materials or other materials to support the restoration of the vegetative cover and enhance the recovery of such areas is limited. The restoration of these areas often requires the use of available amendments such as organic waste products or to help stabilize the soil. Many of the organic waste products, including sewage sludge, clarifier sludge, fly ash sludge, and other by-products from the agricultural industries such as compost can be employed for beneficial uses.

This study looked at the feasibility of applying organic waste products to a mine soil in Montana to increase soil fertility and enhance plant productivity. Waste rock samples were tested for acid forming potential via acid base accounting. Samples cores were constructed and leached with simulated rainwater to determine amendment affect on metal leaching. A greenhouse study was completed to determine the most suitable amendment(s) for the field mine land site. Results from the acid base accounting indicate that acid formed from the waste rock would be neutralized with the alkalinity in the system. Results also show that metals in solution are easily held by organics from the amendments and not allowed to leach in to the surrounding water system. Data from the greenhouse study indicated that the amendment of sewage sludge was most promising. Application of 2% sewage sludge along with 1% sewage sludge plus 1% clarifier sludge, 2% compost, and no treatment were used for mine land application. Initial results were encouraging and it appears that sewage sludge may be a good reclamation option for mine lands.

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EXECUTIVE SUMMARY

Abandoned mine sites have been left as unproductive wastelands, exposing hazards to both human and environmental health.

This study looked at the feasibility of applying organic waste products to a mine soil in Montana to increase soil fertility and enhance plant productivity. Results from the acid base accounting indicate that acid formed from the waste rock would be neutralized with the alkalinity in the system. Results also show that metals in solution are easily held by organics from the amendments and not allowed to leach in to the surrounding water system. Data from the greenhouse study indicated that the amendment of sewage sludge was most promising. Application of 2% sewage sludge along with 1 % sewage sludge plus 1 % clarifier sludge, 2 % compost, and no treatment were used for mine land application. Initial results were encouraging and it appears that sewage sludge may be a good reclamation option for mine lands.

In summary, data from this study suggest that selected synthetic soil amendments used for mining site reclamation at the comet mine site successfully increased plant germination rates and biomass. Sewage sludge amendments appear to be the most effective in enhancing germination and plant biomass production. Evaluation of the existing data and site assessments indicate that amending synthetic soil from sludge materials is a viable technique to facilitate and enhance mining site reclamation.

INTRODUCTION

Abandoned mine sites associated with coal and metal mining across the western United States have been left as unproductive wastelands (Pang et al., 2003, Dutta and Agrawal, 2003). Many are covered with spoil materials that are very acidic and high in toxic elements. These lands are often associated with the contamination of surface water and groundwater resources. The availability of soil materials or other materials to support the restoration of the vegetative cover and enhance the recovery of such areas is limited.

The restoration of areas that have been heavily impacted by mining and the disposal of mine waste require the use of available amendments, fertilizers, and stabilization techniques. Appropriate measures can be taken to enhance the productivity of mine areas by modifying the chemical, physical, and biological characteristics of the available growth media (Nengovhela et al., 2004, Ueshima et al., 2004, Picher et al., 2002). Many of the so called waste products, including, sewage sludge (biosolids sludge and cakes), wood product from paper mills and lumber production, fly ash sludge, and by-products from the agricultural industries (beet limes, manure, and compost) can be employed for beneficial uses. The beneficial use of these products often results in their placement in environments that limit any contribution to environmental degradation as compared to concentrating such materials in land-fills or sludge ponds that can fail, resulting in environmental damage. A number of successes have been documented concerning the use of waste products such as sewage sludge, fly ash, wood products, and other materials to enhance the reclamation of mined lands and the overall productivity of farm lands (Chiu et al., 2006, Xinchao et al., 2005, Reid and Naeth, 2005, Bulusu et al., 2005, Gibert et al., 2005).

Containing organic compounds and other nutrient components, sludge generated from municipal wastewater treatment plants can be a valuable resource rather than a potential pollutant. Sludge can be used as a fertilizer or soil conditioner because of the nutrients it contains. The use of sewage sludge materials as an amendment for improving plant growth on croplands has been well documented (Chiu et al., 2006, Reid and Naeth, 2005, Haveroen et al., 2005, Hemsi et al., 2005, Lopez-Tercero et al., 2005). For example, sludge application to iron-deficient calcareous soils serves as an excellent iron fertilizer (Abbaspour et al., 2004); and zinc and copper, often deficient in soils that have been used to produce crops for many years, can be replaced by sludge application (Afyuni, et al., 2006, Lavada et al., 2005). Analytical results suggest sewage sludge is also a source of phosphorus and organic matter, which are beneficial to soil.

The soil conditioning properties of sludge may have beneficial uses in revegetation of disturbed lands. Municipal sludge has been applied to agricultural lands, forests, and strip mined lands (Lopez-Tercero et al., 2005, Bulusu et al., 2005). Approximately 66% of the sludge applied to land is applied for agricultural crops and pastures, and ten or more states have undertaken sludge application to forest lands. Its use to enhance reclamation has been shown by Skousen (1998), who reported that grass cover and biomass increased as sewage sludge application rates increased. Many other studies have described the beneficial effects of sludge on vegetation productivity (Afyuni et al., 2006, Lavado et al., 2005, Oliver et al., 2005). Investigators have developed productive synthetic soil by amending sewage sludge/cement kiln dust (N-Viro) (Burnham and Logan, 1993) and flue gas desulfurization by-products (Logan, 1993).

Studies have shown that coal combustion by-products remediate plant growth problems related to acid-forming materials. For example, Brown and Bland (1997) used pressurized fluidization bed combustion by-products with significant success to ameliorate acid materials. In fact, materials collected from test burns associated with the Karhla, Finland plant results in better plant growth than ag-lime treated materials.

Wood products generated during paper production have also been shown to be valuable amendments. McCarthy et al. (1995) showed substantial increases in plant cover and productivity on taconite tailings using office waste paper de-inking residue from a pulp facility. A similar material was used by Li and Daniels (1997) to reclaim coal refuse materials at a site in Virginia. Feagley et al. (1994a, 1994b) demonstrated in greenhouse studies that paper mill sludge enhanced the growth of Bermuda grass and clover on mine soils.

Western Research Institute (WRI) worked with the State of Montana Department of Environmental Quality (MT DEQ) to investigate the feasibility of using waste products from various sources to construct synthetic soils for beneficial use. Constituents of the synthetic soils composed of waste products from sewage sludge treatment facilities, coal-fired utilities, and the pulp and paper industry. The synthetic soils were tested for reclamation of hard rock mining as well as coal mining sites in Montana.

MATERIALS AND METHODS

Materials

All chemicals and reagents used for this study were of analytical grade, purchased from Sigma Aldrich (Milwaukee, WI) unless otherwise indicated. The “synthetic soils” were prepared using one or more of the following amendments, including sewage sludge (biosolids) from a sewage treatment plant (Helena, MT), clarifier sludge (wood fibers) from the Smurfit-Stone paper mill located in Missoula, MT, compost (wood + biosolids) from the EKO Compost Company, and sewage sludge from the Billings, MT sewage treatment plant.

Samples Collection

Waste rock samples were collected during two sampling events in Comet mine near Helena, MT. The first six samples were collected from six soil pits that were advanced at random locations along two transects running across the plot area. Each soil pit was carefully described by layer using standard soil methods. Samples were collected from three major zones in the profile and shipped to WRI. Material was contained, sealed, and stored in coolers at 4^oC until used. Material was also kept at field moisture conditions. Chain of custody forms were attached to each sample shipment.

Amendments to construct synthetic soil were collected and shipped to WRI in 5 gallon buckets and stored at $4^{o}C$ until used. Material was contained, sealed, and stored in coolers at $4^{o}C$ until used. Material was also kept at field moisture conditions. Chain of custody forms were attached to each sample shipment.

Sample Characterization

The waste rock material was characterized with regard to coarse fragments, texture and selected chemical parameters such as total carbon, nitrogen, phosphate. Materials were sieved and <1/4 inch portion was used for the greenhouse studies. The waste rock material was also tested for its acid producing potential using acid base accounting (ABA). An evaluation was conducted using pyrite content and neutralization potential to determine if acid could be generated, contributing to acid mine drainage or decreased vegetation productivity. Amendment materials were analyzed to determine total carbon and other nutrient constituents prior to their addition into the corresponding treatments.

Leachate Study

A leachate study was set up using a Trautwein permeameter system. The Trautwein system is a flexible wall permeameter system which can be used to leach soil cores with minimal side flow .The leachate can then be analyzed and groundwater contamination predictions can be made. Sample cores were prepared with waste rock and soil amendments. Samples were leached with 5 pore volumes of simulated rain water. Effluent was collected and analyzed for arsenic (As), copper (Cu), iron (Fe), molybdenum (Mo), lead (Pb), and zinc (Zn).

Greenhouse Study

A greenhouse study was set up to investigate plant biomass production using various synthetic soil amendments. Synthetic soils were prepared in 6-inch square pots. Amendments include sewage sludge, compost, clarifier sludge, fly ash, ag-lime, and chemical fertilizer. Treatment combinations. are listed in Table 1. Amendments were selected because of their potentials in nutrients and mineral contents. Materials such as fly ash were used for the high calcium content and enhancement of pH buffering capacity in soils. Synthetic soil amendments were compared to common practices like ag-liming and chemical fertilizers.

Selection of the synthetic soil materials used in this study was based on the contents of nutrients such as N, P, and carbon. Synthetic soil was added into the waste rock to reach a final concentration at 2% (w/w).

Blue bunch wheatgrass and Regreen were model plants used for this study. These two species are commonly observed in the studying area. Above ground plant biomass was harvested from all treatments and compared on a dry weight basis. Biomass was dried at 80°F for 48 hours. The greenhouse temperature was maintained at 78°F and the plants were watered twice daily, in the morning and late afternoon.

Treatment

Table 1. Greenhouse Study Treatments.

1 – Waste Rock Only	13 – EKO Compost (Dried) + Ag-Lime
2 – Topsoil Material	14 – EKO Compost (Dried) + Fly Ash
3 – Sewage Sludge (Dried)	15 – EKO Compost (Dried) + Fly Ash + Fertilizer
4 – Sewage Sludge + Paper Mill Clarifier Sludge (Dried)	16 – Paper Mill Clarifier Sludge (Dried) + Fly Ash
5 – EKO Compost (Dried)	17 – Paper Mill Clarifier sludge (Dried) + Fly Ash + Fertilizer
6 – EKO Compost (Dried) + Fertilizer	18 – Sewage Sludge
7 – Paper Mill Clarifier Sludge (Dried)	19 – Sewage Sludge + Fly Ash
8 – Paper Mill Clarifier Sludge (Dried) + Fertilizer	20 – Paper Mill Clarifier Sludge
9 – Waste Rock + Fly Ash	21 – Paper Mill Clarifier Sludge + Fly Ash
10 – Topsoil + Ply Ash	
11 – Sewage Sludge (Dried) + Fly Ash	22 – Sewage Sludge + Paper Mill Clarifier Sludge
12 – Sewage Sludge (Dried) + Clarifier Sludge (Dried) + Fly Ash	

An additional greenhouse study was set up using the same conditions to investigate the selected treatment combinations. Four treatment combinations were selected as shown in Table 2. Each pot contained 4 kg of waste rock minus amendment. Western wheatgrass and blue bunch wheatgrass were used for this study. 20 seeds were planted in each pot and watered daily. Seed germination numbers were recorded after one week.

Table 2. Treatments in Additional Greenhouse Study.

Treatment #	Amendment
1	2% Sewage Sludge
2	1% sewage sludge + 1% Clarifier Sludge
3	2% EKO Compost
4	No Treatment

Field Study

The mine site was initially prepared for organic amendment application by using a transit to measure and stake the four corners of two individual test sites. Each site measures 160 feet left to right across the side of the hill by 150 feet top to bottom. One plot is designated the Upper Plot and the other the Lower Plot. A D-6 dozer with a set of three 26-inch long ripping teeth was used to rip the sites. The teeth were two feet apart with an effective ripping depth of 20 inches. Each site was first ripped once across the hill and then once up the hill.

After each site was ripped, the sites were divided into four individual test plots. Three test plots were staked out measuring 50 feet across for the organic amendments and an additional plot was staked out measuring 10 feet across for the control. Each plot runs the full 150-foot length of the site from top to bottom. Additional stakes were placed every 25 feet up and down the sides of each plot for visualization purposes. The layout for each site can be seen in Figure 1 as looking from the bottom of the mountain.

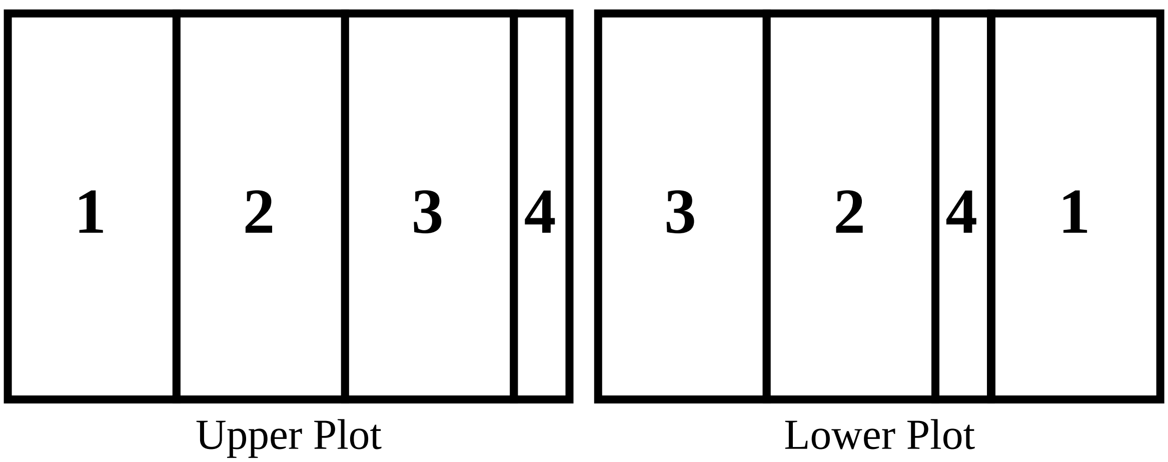

Figure 1. Layout for upper and lower plots.   Treatment #'s inside plot areas.

Each of the 50 foot plots was subdivided into four quadrants for sampling purposes. Each quadrant was then sampled in four diffent locations. Samples in each quadrant were taken in the following mannor: 1) 25 feet from the top of the quadrant and 8 feet from each side resulting in two samples, 2) 25 feet from the bottom of each quadrant and 8 feet from each side resulting in two samples. The four samples were then combined into one sample for analysis resulting in four separate samples for each 50 foot plot. The two 10 foot plots were divided in half and four samples were taken at 18 foot intervals 5 feet from the sides resulting in two separate samples for each 10 foot plot.   One set of samples was taken from each 50 foot plot before the organic amendments were added and then one set of samples was taken after the organic amendments were added. For the 10 foot plots only one set of samples was taken. The samples from the upper plot were labeled with a T for top and the samples from the lower plot were labled with a B for bottom. Initial organic samples were also taken from each plot before mixing. Sampling layout is shown in Figure 2.

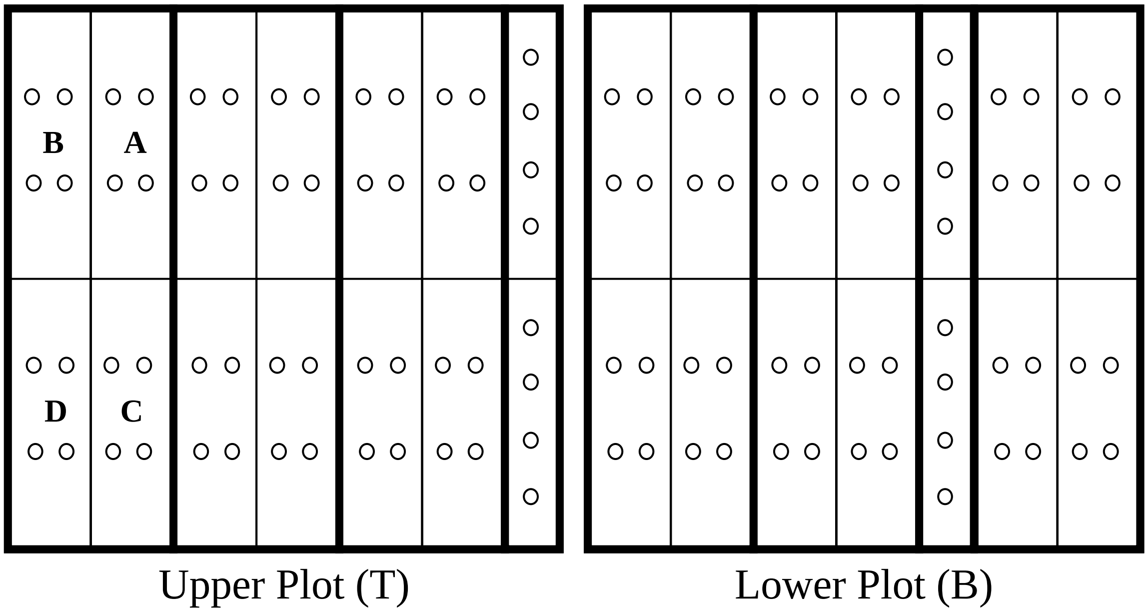

Figure 2. Sampling layout for upper and lower plots.

Organic amendments were added using a loader with a weighing device on the bucket. Individual loads were weighed and then placed on the corresponding plot until the desired amount was achieved. The organic amendments were then incorporated into each plot using a D-6 dozer. The dozer mixed the organic amendments with the waste rock and then spread the mixed material evenly throughout the plot. The plot was then smoothed in preperation for planting. Tables 3 and 4 show the organic amendments for each plot and amounts applied.

Table 3. Organic amendment amounts applied to the upper (T) plot.

Treatment #	Amendment	Amount, tons
1	Compost	14.1
2	Sewage Sludge + Clarifier Sludge	6.8 + 4.9
3	Sewage Sludge	13.3

Table 4. Organic amendment amounts applied to the lower (B) plot.

Treatment #	Amendment	Amount, tons
1	Compost	14.0
2	Sewage Sludge + Clarifier Sludge	6.8 + 5.3
3	Sewage Sludge	13.3

Field Sampling and Laboratory Analysis

Samples taken back to the lab were air dried and seived through a ¼-inch sieve. All the organic amendments above 1/4-inch were removed from the sieve and added to the sample. The samples were then taken to the Soil, Water and Plant Testing Laboratories in Fort Collins, CO. A sludge screen was run on the initial organic samples and a soil monitoring analysis was run on the soil samples.

RESULTS AND DISCUSSION

Sample Characterization

One of the primary concerns of using waste rock as a top dressing material is its potential to produce acid. As the ABA data in Table 5 shows, the tendency is for any acid formed to be neutralized by the alkalinity present in the system. Therefore, acid would not be expected to cause reclamation problems at the mine site.

Table 5. Potential for the waste rock material to form acidity

Sample ID	Neutralization Potential, t/1000t	Pyritic Sulfur, %	Potential Acidity, t/1000t	Acid Base Accounting, t/1000t
C-1-1	43.0	.011	3.44	39.56
C-1-2	30.2	0.25	7.81	22.39
C-1-3	41.5	0.21	6.56	34.94
C-2-1	26.0	0.23	7.19	18.81
C-2-2	18.6	0.08	2.50	16.10
C-2-3	19.1	0329	9.06	10.04
C-3-1	37.1	0.46	14.40	22.70
C-2-2	36.1	0.45	14.40	21.70
C-3-3	34.7	.052	16.20	18.50
C-4-1	70.9	0.90	28.10	42.80
C-4-2	31.8	0.42	13.10	18.70
C-4-3	29.4	0.48	15.00	14.40
C-5-1	49.6	0.56	17.50	32.10
C-5-2	37.9	0.33	10.30	27.60
C-5-3	35.9	0.83	25.90	10.00
C-6-1	54.0	0.57	20.90	33.10
C-6-2	54.0	0.28	8.75	45.25
C-6-3	64.9	0.23	7.19	57.70

Leachate Study

Leaching characteristics are key parameters to the success of a synthetic soil. Water leached through columns of waste rock and waste rock treated with organic amendments was analyzed to determine the potential impact the organic amendments might have on the metals leaching from the materials. The solutions leached from the treated materials were characterized and the averages are shown in Table 6.

Table 6. Impact of bio-solids on the levels of metals found in treatment leachate.

Waste Rock Sample	As, ppm	Cu, ppm	Fe, ppm	Mo, ppm	Pb, ppm	Zn, ppm
No treatment	25.4	26.4	65.4	12.0	95.8	135
Biosolids treatment	0.20	<0.02	<0.05	0.06	<0.02	1.35

Substantial reductions in all metals were observed for all biosolids treatments. The leachate collected from the untreated waste rock contains high levels of metals compared to the leachate collected from the waste rock treated with biosolids. This data demonstrates the sorption of metals to organic matter in the amended rock waste, therefore reducing or preventing the metals from leaching into receiving water bodies.

Greenhouse Study

Effects of synthetic soil amendments on seed germination and plant biomass production were investigated in the Greenhouse study. Germination of seeds was visually counted as recorded in Tables 7 and 8. The germination rates are summarized and presented in Figures 3-5 for the two plant species studied.

Results of plant seed germination study for Regreen grass are presented in Figure 3. The germination rates of the Regreen grass species seemed to be consistent across all treatments. In fact, waste rock without treatment showed a higher germination rate among the treatments with synthetic soil amendments. The data does not show any significant influence the synthetic soil amendments have on Regreen seed germination. In the meantime, no apparent toxicity was observed in the amendments that may limit germination.

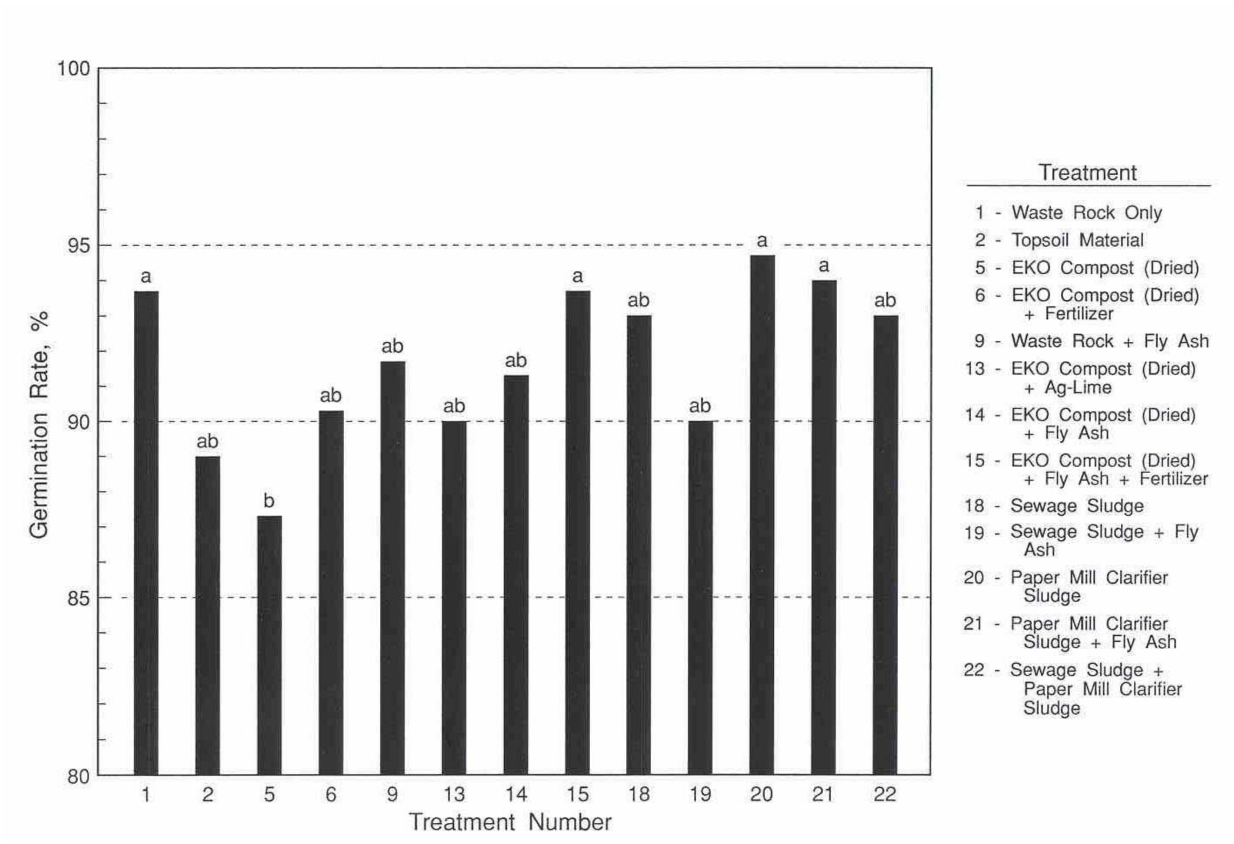

Figure 3. The Influence of Amendment on Germination Rate of Regreen

Results from the tests on the Blue Bunch Wheatgrass are presented in Figure 4. Similar to the data obtained from Regreen study (Figure 3). Synthetic soil amendments did not show significant influence on germination rate, as shown in Figure 4 In most treatments, including non-amended controls (1), germination rates ranged from 80-93%. In the topsoil treatment, germination rate was 62%. Presumably the carbon rich top soil decreased the microbial activities in the top soil amendments due to imbalanced C:N ratio, resulting in the nutrient shortage for seed germination. This result is unexpected and the mechanisms are to be determined through further research. Germination rates in wet sewage sludge treatment ranged from 75 to 88%. The higher levels of ammonia in the wet sludge might have had an impact on germination. The dry sewage sludge did not show any adverse effect on germination, presumably the volatile ammonia was lost during the drying preparation of the materials.

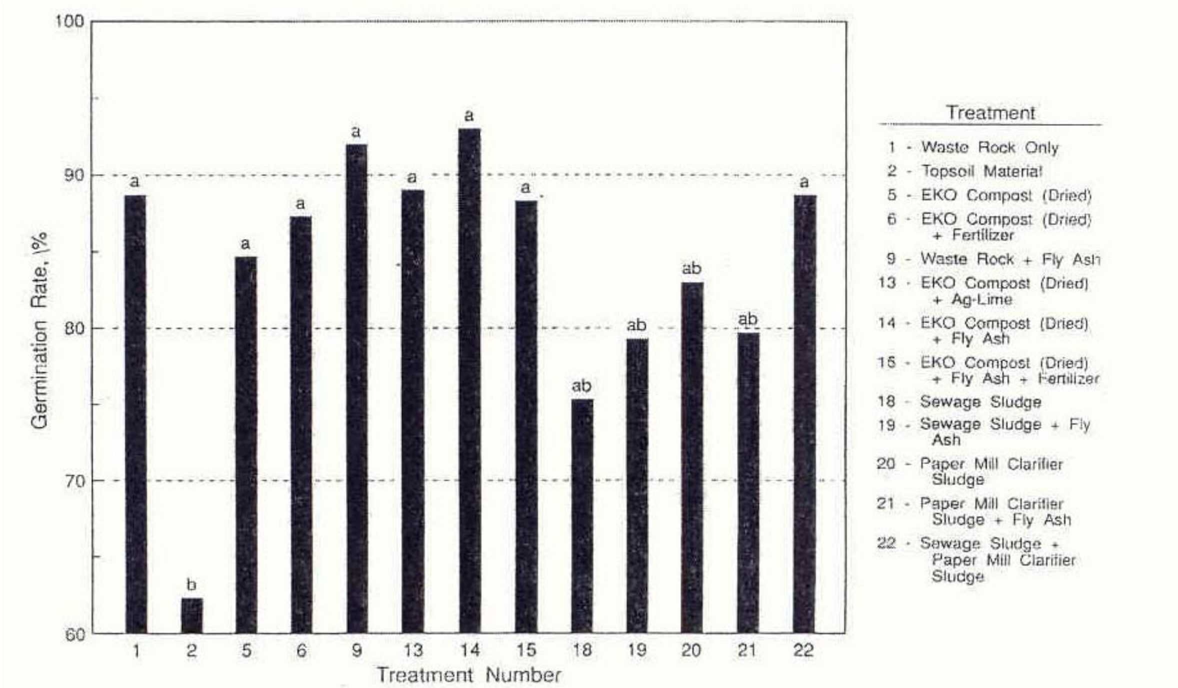

Figure 4. The Influence of Amendment on Germination Rate of Blue Bunch Wheatgrass

Results from the first cutting of the Regreen grass are presented in Figure 5. Results show sewage sludge amendments (Treatments 18 and 22) averaged approximately 20% higher plant biomass production on a dry weight basis when compared to the next highest production in the topsoil treatments (Treatments 2 and 10). The clarifier sludge amendment (Treatments 7, 8, 16 and 17) contributed to the least improvement of biomass production The compost amendment in Treatments 5, 6, 13, 14 and 15 outperformed the clarifier sludge slightly in the biomass enhancement.

Both the clarifier sludge and compost treatments were expected to produce lower plant biomass because of the high C:N ratio in them. A high C:N ratio may decrease microbial activity and as a result decreased mineralization and availability of important nutrients for plant growth. In addition, the results indicate that fly ash amendment may be detrimental to plant biomass production. With the exception of the topsoil and waste rock only, the addition of fly ash decreased biomass production when combined with another amendment and compared to that amendment without fly ash. Mechanisms that contributed to the inhibition of fly ash to plant growth are to be determined.

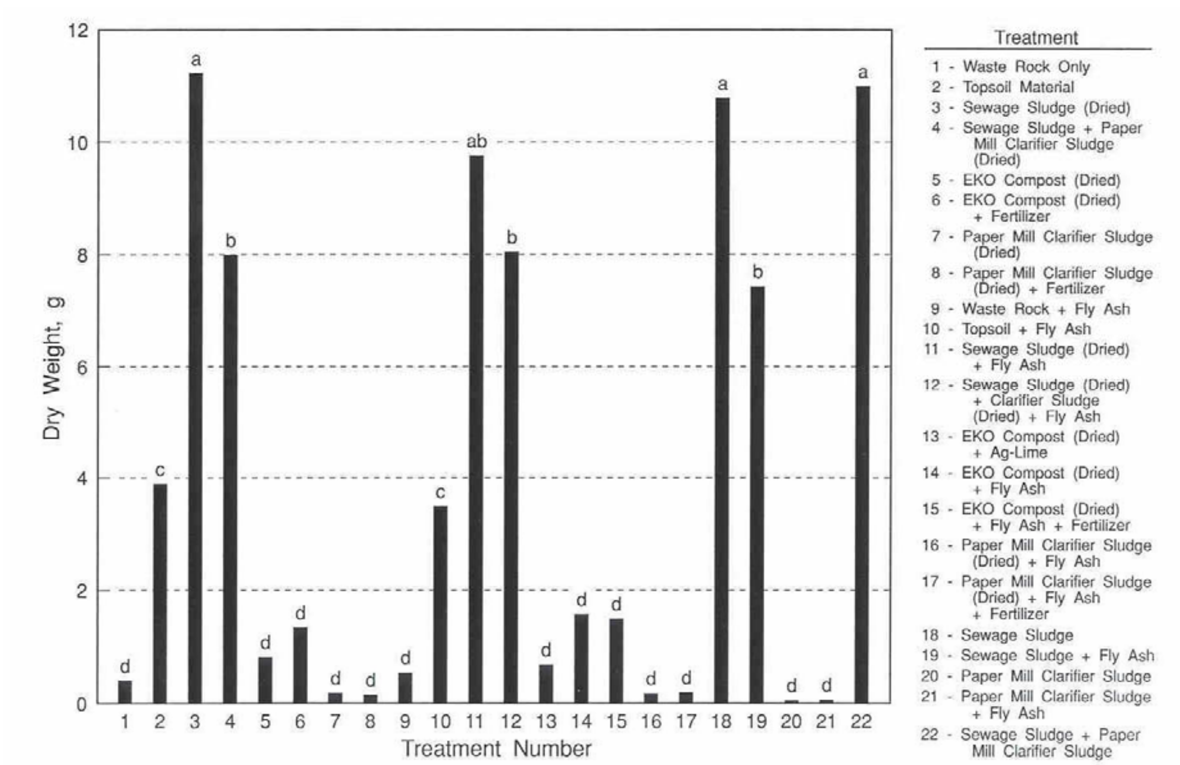

Figure 5. Influence of Amendment on Biomass of Regreen (1st cutting, 5/1/99)

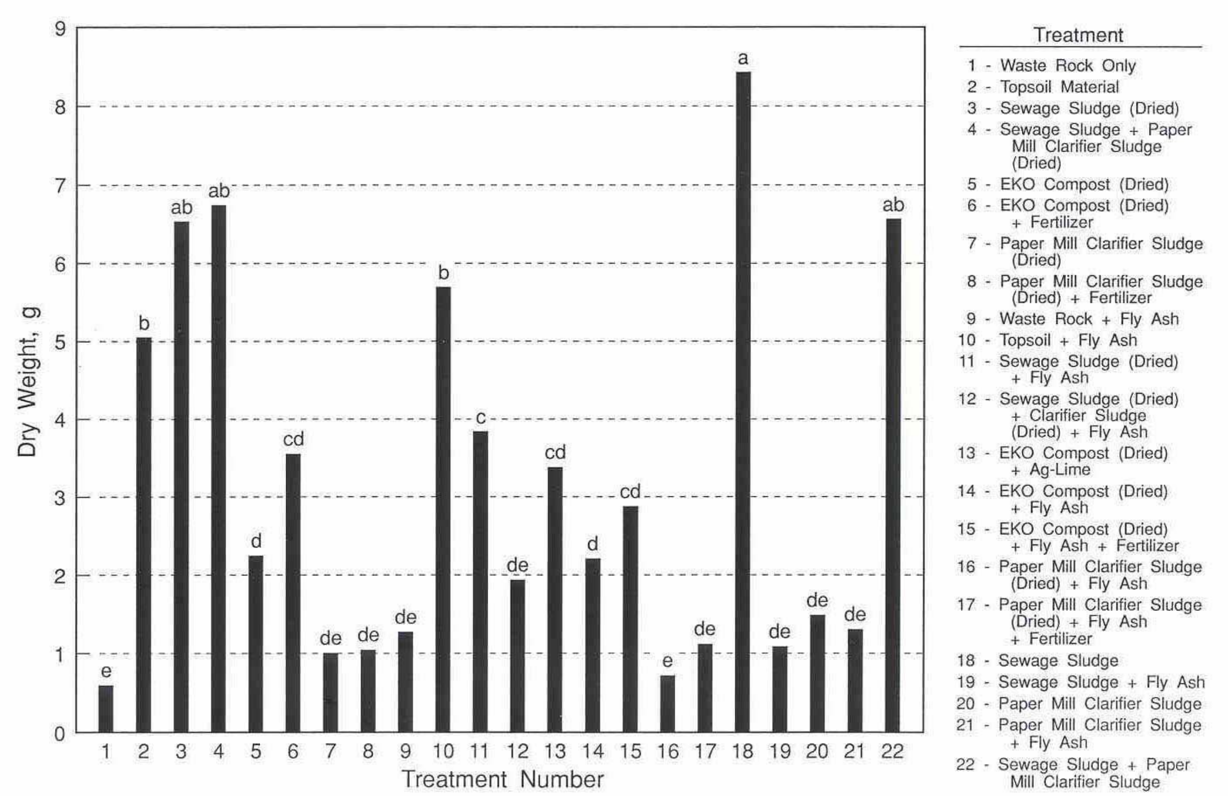

Figure 6. Influence of Amendment on Biomass of Regreen (2nd cutting, 7/6/99 and 7/12/99)

Results from the second cutting for Regreen grass are presented in Figure 6. Similar observations were obtained as the data from the first cutting (Figure 5); however clearer effects of amendment on biomass production can be observed. The topsoil and sewage sludge amendments demonstrate significant enhancement on biomass production. Apparently these amendments can sustain the supply of essential plant nutrient for biomass production. The compost and clarifier sludge amendments are not as effective as sewage sludge and topsoil in increasing biomass, and the trend is consistent as in the data from the first cutting (Figure 5).

In both cuttings of the Regreen study, germination rates in the non-amendment rock controls are the lowest, indicating most amendments have positive influence in the seed germination in the plants under study.

Results from the first cutting of the Blue Bunch wheatgrass are presented in Figures 7. Blue bunch wheatgrass is a slower growing grass, and as a result, the time of the first cutting was not until the second cutting of Regreen. The data obtained in the Blue Bunch wheatgrass well agree with that from the Regreen study. Sewage sludge amendments (Treatments 18 and 22) averaged approximately 800% higher plant biomass production on a dry weight basis when compared to the non-amended controls (Treatment 1).

In general, the treatments that included an application of sewage sludge were significantly higher in biomass when compared to the other treatments. The only discrepancy to this generalization is the treatments including clarifier sludge and fly ash (Treatment 12) tend to show significantly less enhancement in biomass when compared to treatments containing sewage sludge (Treatments 4, 18, and, 22). Obviously the fly ash amendments were detrimental to plant growth in this experiment. Data also show that treatments using EKO compost and clarifier sludge without the addition of sewage sludge have less enhancing effect in biomass production. The low levels of N in these amendments could not sustain good plant growth through the second cutting.

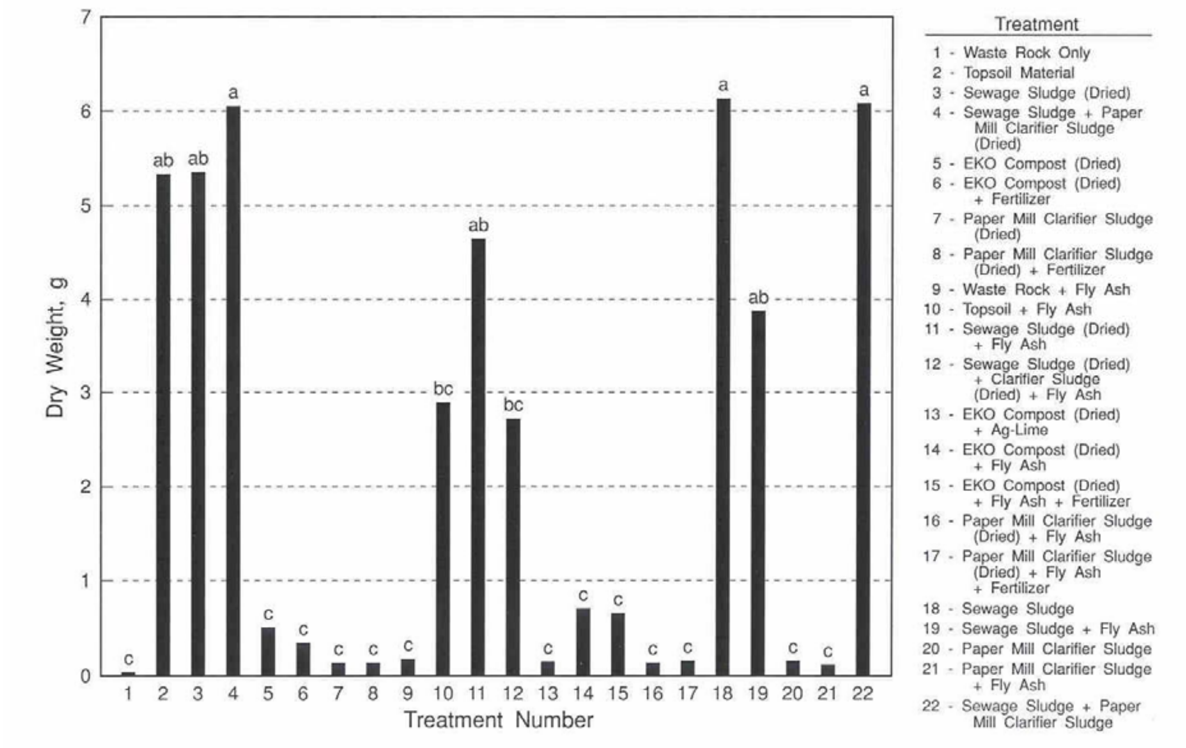

Figure 7. Influence of Amendment on Biomass of Blue Bunch Wheatgrass (first cutting, 7/6/99 and 7/12/99)

Photographs showing plants associated with waste rock only (Treatment 1), sewage sludge only (Treatment 18), EKO compost only (Treatment 5), and a comparison between sewage sludge dried only (Treatment 3) and EKO Compost (Treatment 5) are presented in Figure 8. Visual observations indicate that the sewage sludge resulted in much higher plant mass production as compared to the control and to EKO Compost.

Waste Rock Only

EXO Composite

Sewage Sludge

Sewage Sludge (dried) - left
EKO Compost (dried) - right

Figure 8. Plant Biomass with Different Amendments.

CONCLUSIONS

Data from this study suggest that selected synthetic soil amendments used for mining site reclamation at the comet mine site successfully increased plant germination rates and biomass. Sewage sludge amendments appear to be the most effective in enhancing germination and plant biomass production. EKO compost and clarifier sludge showed the least effect on plant biomass production. Fly ash obviously is not a suitable amendment to improve the reclamation of mining sites through vegetation coverage.

Evaluation of the existing data and site assessments indicate that amending synthetic soil from sludge materials is a viable technique to facilitate and enhance mining site reclamation.

ACKNOWLEDGEMENT

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Table 7. Greenhouse Study Germination Data. - Western Wheatgrass in Comet Waste Rock

Date	T1-A-1	T1-A-2	T1-A-3	T2-A-1	T2-A-2	T2-A-3	T3-A-1	T3-A-2	T3-A-3	T4-A-1	T4-A-2	T4-A-3
2/7/01	Planted	Planted	Planted	Planted	Planted	Planted	Planted	Planted	Planted	Planted	Planted	Planted
2/14/01	0	1	0	1	0	0	3	1	0	0	0	0
2/15/01	1	1	1	1	0	0	6	5	0	0	0	0
2/16/01	1	2	2	4	1	2	7	7	0	0	0	0
2/17/01	3	4	8	5	2	7	8	10	0	2	0	0
2/18/01	5	9	13	10	6	10	14	14	0	4	0	0
2/19/01	7	10	16	10	8	10	14	14	1	6	1	0
2/20/01	9	12	16	11	10	12	14	14	2	7	3	0
2/21/01	9	12	17	11	11	13	14	14	3	11	4	0
2/22/01	9	13	17	13	11	15	14	15	4	12	5	5
2/23/01	11	13	17	16	11	17	16	15	16	13	8	8
2/24/01	11	13	17	16	12	17	16	15	16	14	9	10
2/25/01	12	13	17	16	13	17	16	16	16	14	12	11
2/26/01	12	13	17	16	13	17	16	16	17	15	14	13
2/27/01	12	14	17	15	13	17	17	16	17	15	15	13
2/28/01	13	14	18	16	12	17	17	16	17	15	15	15
3/1/01	14	14	18	16	13	17	17	16	17	15	15	16
3/2/01	14	14	18	17	13	17	17	16	17	15	15	17
3/3/01	14	14	18	17	13	17	17	16	17	15	16	17
3/4/01	14	14	17	17	14	17	17	16	17	15	16	17
3/5/01	14	14	17	17	14	17	17	16	17	15	16	17
3/6/01	14	14	17	17	14	17	17	16	18	15	16	17
3/7/01	14	14	17	17	14	17	17	16	18	15	16	17
3/8/01	14	14	17	17	14	17	17	16	18	15	16	17
3/9/01	14	14	17	17	14	17	17	16	18	15	16	17
3/12/01	14	14	17	15	12	17	17	15	18	15	16	17
3/19/01	13	14	17	15	12	17	17	15	18	15	16	17
3/26/01	13	15	17	15	12	17	17	15	18	15	16	17
4/2/01	13	16	17	15	11	17	17	15	18	15	16	17
4/9/01	13	14	17	15	11	15	17	15	17	15	16	17

Table 8. Greenhouse Study Germination Data – Bluebunch Wheatgrass in Comet Waste Rock

Date	T1-B-1	T1-B-2	T1-B-3	T2-B-1	T2-B-2	T2-B-3	T3-B-1	T3-B-2	T3-B-3	T4-B-1	T4-B-2	T4-B-3
2/7/01	Planted	Planted	Planted	Planted	Planted	Planted	Planted	Planted	Planted	Planted	Planted	Planted
2/14/01	2	2	1	0	0	1	0	0	0	0	0	0
2/15/01	5	3	2	0	5	1	1	0	0	0	0	0
2/16/01	9	4	5	3	7	4	4	3	0	0	0	0
2/17/01	11	5	7	3	7	6	4	5	3	0	1	2
2/18/01	14	10	10	4	10	9	6	8	7	0	1	6
2/19/01	15	12	11	4	12	10	7	9	10	0	2	10
2/20/01	15	13	12	5	12	10	7	11	10	0	4	11
2/21/01	16	13	12	5	12	12	7	13	10	0	5	12
2/22/01	17	13	12	5	12	12	7	13	10	2	5	12
2/23/01	17	13	12	6	12	13	8	13	10	3	5	12
2/24/01	17	13	14	6	12	12	8	13	10	4	8	12
2/25/01	16	13	12	6	12	12	8	13	10	5	10	13
2/26/01	16	13	12	6	12	12	8	13	10	7	12	13
2/27/01	16	13	12	6	12	12	8	13	10	7	13	13
2/28/01	16	13	12	6	12	12	8	14	10	8	13	13
3/1/01	16	13	12	6	12	12	9	14	10	10	13	13
3/2/01	17	13	12	6	12	11	9	13	11	10	14	12
3/3/01	16	13	12	6	12	11	9	13	10	11	14	12
3/4/01	16	13	12	6	12	11	9	13	10	11	14	12
3/5/01	16	13	12	6	12	11	9	13	10	12	14	12
3/6/01	16	13	11	6	12	11	9	13	10	12	14	12
3/7/01	16	13	11	6	12	11	9	13	10	12	14	12
3/8/01	16	13	11	6	12	11	9	13	10	12	14	12
3/9/01	16	12	11	6	12	11	9	13	10	12	14	12
3/12/01	15	9	11	6	12	11	9	12	10	12	12	12
3/19/01	14	8	11	5	12	11	9	12	10	12	12	12
3/26/01	14	6	11	5	12	11	9	12	10	12	12	11
4/2/01	14	6	11	5	12	11	9	12	10	11	12	11
4/9/01	13	4	9	5	12	10	9	12	10	11	12	11

REFERENCES

Brown, T.H., and A.E. Bland. 1997 "Pressurized Fluidized Bed Combustion Ash: Part II-Soil and Mine Spoil Amendment Use Options."; *Fuel* 76(8): pp 741-748.

Burnham, J., and T. Logan. 1993 "N-Vitro Soil: Advanced Alkaline Sludge Stabilization,"; *Proc., 10th National Meeting of the ASSMR*, May 16-19, 1993, Spokane, Washington. pp 765-783.

Feagley, S.E., M.S. Valdez, and W.H. Hudnall. 1994a. "Papermill Sludge, Phosphorus, Potassium, and Lime Effect on Clover Grown on Mine Soil"; *J. Environ. Qual. 23,* pp 759-765.

Feagley, S.E., M.S. Valdez, and H.W. Hudnall. 1994b. "Bleached Primary Papermill Sludge Effect on Bermuda Grass Grown on a Mine Soil"; *Soil Science 157* pp 389-397.

Li, R.S., and W.L. Daniels. 1997. "Reclamation of Coal Refuse with a Papermill Sludge Amendment"; pp 277-290. *Proc*., *14th National Meeting of the ASSMR*, Austin, TX, May 10-15, 1997

Logan, T. 1993. "Mine Spoil Reclamation with Sewage Sludge Stabilized with Cement Kiln Dust and Flue Gas Desulfurization Byproduct (N-Vitro Soil Process)"; *Proc*., *10th National Meeting of the ASSMR*, Spokane, WA, May 16-19, 1993, pp 784-795

McCarthy, B.J., S.D. Monson Geerts, K.W. Johnson, and T.J. Malterer. 1995. "Mine Land Reclamation Using Office Waste Paper De-inking Residue." *Proc*., *12th National Meeting of the ASSMR*, Gillette, WY. June 3-8, 1995, pp 93-104

Skousen, J. 1988. "Effects of Sewage Sludge Application on a Revegetated Mine Soil in West Virginia." *Proc., Mine Drainage and Surface Mine Reclamation conference, Volume II: Mine Reclamation, Abandoned Mine Lands and Policy Issues, U.S. Bureau of Mines Information Circular IC 9184*, pp 214-220.

Oliver, I.W., M.J. McLaughlin, G. Merrington, "Temporal Trends of Total and Potentially Available Element Concentrations in Sewage Biosolids: a Comparison of Biosolid Surveys Conducted 18 Years Apart." *Science of the Total Environment*, Vol. 337 Issue 1-3, January, 2005, pp 139-145

Lavado, R.S., M.B. Rodruquez, M.A. Taboada, "Treatment with Biosolids Affects Soil Availability and Plant Uptake of Potentially Toxic Elements"; *Agriculture, Ecosystems & Environment*, Vol. 109 Issue 3/4, September 2005, pp 360-364

Afuni, M., Y. Rezaeinejad, R. Schulin, "Extractability and Plant Uptake of Cu, Zn, Pb and Cd From a Sludge-Amended Haplargid in Central Iran"; *Arid Land Research & Management,* Vol. 20 Issue 1, Jan-Mar 2006, pp29-41

Abbaspour, A., M. Kalbasi, H. Shariatmadari, “Effect of Steel Converter Sludge as Iron Fertilizer and Soil Amendment in Some Calcareous Soils”; *Journal of Plant Nutrition*, Vol. 27 Issue 2, February 2004, pp 377-394

Lopez-Tercero, A.M., M.L. Andrade, P. Marcet, “Organic Nitrogen Mineralization Rate in Sewage Sludge-Amended Mine Soil”; *Communications in Soil Science & Plant Analysis*, Vol. 36 Issue 7/8, 2005, pp1005-1019

Hemsi, P.S., C.D. Shackelford, L. Figueroa, “Modeling the Influence of Decomposing Organic Solids on Sulfate Reduction Rates for Iron Precipitation”; *Environmental Science & Technology*, Vol. 39 Issue 9, May 2005, pp3215-3225

Haveroen, M.E., M.D. MacKinnon, P.M. Fedorak, “Polyacrylamide Added as a Nitrogen Source Stimulates Methanogenesis in Consortia From Various Wastewaters”; *Water Research*, Vol. 39 Issue 14, September 2004, pp 3333-3341

Chiu, K.K., Z.H. Ye, M.H. Wong, “Growth of Vetiveria Zizanioides and Phragmities Australis on Pb/Zn and Cu Mine Tailings Amended with Manure Compost and Sewage Sludge: A Greenhouse Study”; *Bioresource Technology*, Vol. 97 Issue 1, pp158-170

Reid, N.B., M.A. Naeth, “Establishment of a Vegetation Cover on Tundra Kimberlite Mine Tailings: 1. A Greenhouse Study”; *Restoration Ecology*, Vol. 13 Issue 4, December 2005, pp 594-601

Gibert, O., J. dePablo, J.L. Cortina, C. Ayora, “Municipal Compost-Based Mixture for Acid Mine Drainage Bioremediation: Metal Retention Mechanisms”; *Applied Geochemistry*, Vol. 20 Issue 9, September 2005, pp 1648-1657

Bulusu, S., A.H. Aydilek, P. Petzrick, R. Guynn, “Remediation of Abandoned Mines Using Coal Combustion By-Products”; *Journal of Geotechnical & Geoenvironmental Engineering*, Vol. 131 Issue 8, August 2005, pp958-969

Xinchao, W., R.C. Viadero Jr., K.M. Buzby, “Recovery of Iron and aluminum from Acid Mine Drainage by Selective Precipitation”; *Environmental Engineering Science*, Vol. 22 Issue 6, November 2005, pp 745-755

Picher, S., P. Drogui, R. Guay, J.F. Blais, “Wastewater Sludge and Pig Manure Used as Culture Media for Bioleaching of Metal Sulphides”; *Hydrometallurgy*, Vol. 65 Issue 2/3, September 2002, p177

Ueshima, M., K. Fortin, M. Kalin, “Development of Iron-Phosphate Biofilms on Pyritic Mine Waste Rock Surfaces Previously Treated with Natural Phosphate Rocks”; *Geomicrobiology Journal*, Vol. 21 Issue 5, July/August, 2004, pp313-323

Nengovhela, N.R., C.A. Strydom, J.P. Maree, H.A. Greben, “Chemical and Biological Oxidation of Iron in Acid Mine Water”; *Mine Water & the Environment,* Vol. 23 Issue 2, August 2004, pp 76-80

Pang, J., G.S.Y. Chan, J. Zhang, J. Liang, M.H. Wong, “Physiological Aspects of Vetiver Grass for Rehabilitation in Abandoned Metalliferous Mine Wastes”; *Chemosphere,* Vol. 52 Issue 9, September 2003, p1559

Dutta, R. K., M. Agrawal, “Restoration of Opencast Coal Mine Spoil by Planting Exotic Tree Species: A Case Study in dry Tropical Region”; *Ecological Engineering,* Vol. 21 Issue 2/3, December 2003, p143