RECLAMATION OF SITE NEAR A SMELTER USING SLUDGE/FLY ASH AMENDMENTS: HERBACEOUS SPECIES[1]

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Abstract.--Emissions from two zinc smelters in Carbon County, PA, over an 80-year period caused the defoliation of nearby Blue Mountain. High levels of SO_2 slowly killed off the existing oak-chestnut forest and particulate metals built to very high levels in the soil. Current metals levels in the soil are as high as 1,300 ppm Cd; 6,474 ppm Pb; and 32,085 ppm Zn. These high levels have stopped microbial activity, and there has been no decomposition or regeneration for decades. The site is now on the EPA Superfund clean-up list. Both physical and chemical problems with the eroded soil need to be addressed to reclaim this site. The hypothesis tested was to use mixtures of sludge and fly ash, lime and potash to revegetate the site using metals-tolerant ecotypes of herbaceous species. Three ratios of sludge: fly ash were used (1:1, 2:1, and 3:1) on a volume basis. The sludge amount was a constant, based on the desired loading rate of N (2,100 kg/ha). The amendments were blown onto the site and not incorporated. Species used were 1) switchgrass, Panicum virgatum, 2) big bluestem, Andropogon gerardi, 3) tall fescue, Festuca arundinacea, plus birdsfoot trefoil, Lotus corniculatus, 4) flatpea, Lathyrus sylvestris, plus perennial ryegrass, Lolium perenne, and 5) intermediate wheatgrass, Elytrigia intermedia. Results in 1986 and 1987 were excellent with the 1:1 ratio being slightly superior across all species. This new reclamation technology may be applicable to a number of drastically disturbed areas.

INTRODUCTION

Zinc smelting has taken place in Palmerton, Carbon County, PA, since 1898. Two smelters, the second beginning operation in 1912, located at the base of Blue Mountain, operated continuously until 1980, when primary zinc smelting was terminated. Emissions from the smelters, both from the coal-fired physical plant and from the roasting, sintering, and smelting of zinc sulfide ores contributed to the defoliation of several thousand acres of adjacent land (Buchauer 1971, Jordan 1975).

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During the years of active smelting, very high levels of SO_2 were emitted into the atmosphere. In 1962, SO_2 emissions varied between 3,300 and 3,600 lb/hr, and it has been assumed that this rate had been essentially the same since 1918, since there had been no major process changes (PADER 1987). By 1970, SO_2 emissions had declined to an average of 1,400 lb/hr(Buchauer 1971). Particulates of cadmium, lead and zinc were also emitted, which built up in the soil at extreme levels. Historic estimates of total metals emitted are: cadmium - 3,740 tons or 47 tons/year; lead - 7,560 tons or 95 tons/year; and zinc - 286,000 tons or 3,575 tons/year (USEPA 1987).

In addition to the pollutants being emitted from the smelters, Blue Mountain has a history of burns and logging. By the time the original forest was killed by the SO_2, there were high enough levels of Cd, Pb, and Zn in the soil to prevent regeneration. Metals levels are so high that microbial activity has ceased, and trees that have been dead for 20 or more years cannot decompose.

Typical soil concentrations of zinc range from 10 to 300 ppm (Brady 1974), while concentrations measured on Blue Mountain varied between 26,000 ppm (Strojan 1978) to 80,000 ppm (Jordan 1975). Typical soil concentrations of cadmium range from 0.1 to 7.0 ppm (Brady 1974), and concentrations measured on Blue Mountain range from 900 ppm (Strojan 1978) to 1,500 ppm (Jordan 1975). Lead has been reported in concentrations as high as 6,474 ppm (Sopper and Oyler 1985).

Following the death of the forest, severe soil erosion occurred, and to date it appears that between 12 and 24 inches of topsoil have been removed from the site. As the soil eroded, rock layers emerged, slowing further movement. The metals levels in the upper 6 to 8 inches of soil remain at toxic levels, however.

In 1982, the U.S. Environmental Protection Agency placed this site on the National Priorities List (Superfund) for toxic site clean-up. Numerous remedial alternatives were evaluated, including removal of the top 12 inches of contaminated soil. Removal cost , without revegetation, was estimated at $1.3 billion (USEPA 1987). In addition to the contaminated soils on the mountain, there are approximately 33,000,000 yds^3 of metal-laden smelting residues in a bank 2-1/2 mi. long at the base of the mountain. Removal cost estimates for the cinder bank range from $1.5 to $2.8 billion, and could take from 29 to 45 years to complete, assuming there would be a place to dispose of it. Because of the unreasonably high environmental and economic costs associated with removal, it was decided to attempt to stabilize the metals on-site through proper pH management and revegetation.

There are many similar problems associated with smelter emissions in the United States and abroad. Gale and Wixson (1979), Wixson and Bennett (1975), Jackson and Watson (1977), Jennett et al. (1977), Jennett and Foil (1979), Kearney et al. (1981), and Bolter et al. (1975) all report very similar problems with zinc and cadmium pollution associated with lead and zinc smelting operations in and around Iron County, MO. Walsh and Bissell (1979) report sulfur dioxide and heavy metal damage to the forests in the vicinity of a copper smelter near Anaconda, MT. In the vicinity of a smelter in Kellogg, ID, Ragaini et al. (1977), Hansen and Mitchell (1978), and Carter and Loewenstein (1978), all report great quantities of SO_2, Zn, Cd, and Pb having been emitted during the smelting process, thus causing total destruction of nearby vegetation.

PAST REVEGETATION ATTEMPTS

Numerous attempts have been made to establish vegetation, both herbaceous and woody, on the contaminated soils of Blue Mountain, and at most of the other similar sites (Buchauer 1971, 1973, Jordan 1975, Soil Conservation Service 1977, 1978, 1979, 1980-81, 1982, 1983, Goodman et al. 1976, Goodman and Gemmell 1978, Hansen and Mitchell 1978.), and none were successful. These studies all demonstrated that conventional reclamation techniques were not capable of revegetating sites so drastically disturbed. Of the work done thus far on Blue Mountain, only two species of plants are surviving: 1) 'Merlin' red fescue, *Festuca rubra*, a proprietary cultivar from England that is priced far too high to be economical; and 2) common thrift, *Armeria maritima*, a species introduced from Norway that has limited conservation value and no commercial seed source, thus precluding large-scale use. Within the plots of the above listed species, even though the plants are surviving, there appears to be no significant insect or microbial activity, which raises doubts concerning long-term ecosystem stability.

Blauel and Hocking (1974), in concluding a multi-year study of the effects of air pollution and forest decline near a nickel smelter in Thompson, Manitoba, state that reclamation of land contaminated by smelter emissions would be an extremely complex and expensive proposition. The practical difficulty with reclamation is that errors in any of a number of steps in the operation can cause either temporary or permanent failure of the operation. Blauel and Hocking (1974) continue: "Besides sulfur, at Thompson the emissions include substantial amounts of arsenic, selenium, cadmium, lead, cobalt, nickel, copper, and zinc... The entry of these elements into the soil chemical and biological cycles constitutes initiation of major site degradation, because they cannot be 'neutralized' or removed easily. They could make extremely difficult or futile any reclamation attempts by currently known methods, and they would add substantially to the costs."

Goodman (1974) and Mills (1985) present the main environmental factors that inhibit or prevent growth of vegetation on waste materials from both the coal and metal industries. The conditions shown in table 1 apply to the Blue Mountain site.

Although most of these are physical problems, the research completed to date around smelter sites relates the failure to establish vegetation primarily to the excess of toxic metals in the soil. Most of the research previously cited has indicated that seedlings would emerge, but not survive past the 2- to 4-inch growth stage.

Table 1.--Conditions inhibiting or preventing revegetation of coal and metal industry wastes and projected solutions provided by innovative sludge/fly ash treatment.

Problem*	Solution
Physical:	
Eroded slopes	Revegetation
Very steep slopes	Spray
Inhibitory water regimes	Sludge, fly ash, mulch retain moisture
Compaction/cementation	Sludge/fly ash mix remains porous
Inhibitory surface temperatures	Light color of fly ash
Wind turbulence (sandblasting)	Sludge/fly ash mix remains stable
Absence of fine materials	Fly ash (soil-sized particles)
Broken, uneven surface	Spray on amendments
Chemical and Biological:	
High levels of toxic elements	Lime/fly ash
Macronutrient deficiency	Sludge (N+P), potash (K)
Micronutrient deficiency	Sludge/fly ash
Absence of soil microflora and fauna	Sludge

*From Goodman (1974) and Mills (1985).

Rationale of Sludge/fly Ash Treatment

The approach to this study was to recognize that the physical problems on smelter-contaminated soils or other similar areas are as important as the toxic amounts of metals. Consequently, steps were taken to mitigate or ameliorate the physical problems and to select metals-tolerant ecotypes of desired species.

In 1984, it was proposed to the U.S. Environmental Protection Agency to attempt the reclamation of Blue Mountain in a manner never before tried. With the backing of the EPA due to the Superfund status of the site, an important new option now became available. This option was that some new and innovative approaches to reclamation could be tried that might be outside the permit requirements of state or local environmental regulatory agencies.

It was proposed to undertake greenhouse and field studies to determine the technical feasibility of reclaiming Blue Mountain using applications of limestone, potash, sewage sludge, and power plant fly ash as soil amendments, and then hydroseeding and mulching adapted species. Due to the extreme slopes on the hillsides, and due to the large amounts of dead trees and the rocky surface conditions, it was also proposed that the amendments be blown onto the soil surface and not incorporated. The assumption was that the amendments would wash off the dead trees and rocks into the "interstitial space" of exposed soil, which averaged 53%, and that vegetation would keep the new soil on site. Reclamation work of this nature is without precedent in the literature. Large amounts of literature are available on the use of either sludge or fly ash for land reclamation, but in all cases, the amendments were incorporated in the spoil material. The use of sludge and fly ash mixed together has been attempted only in greenhouse studies and only with incorporation into uncontaminated soils (Adriano and Page 1981, Adriano et al. 1982, and Adriano et al. 1982a).

The problems of alkalinity and high soluble salts that were identified in these studies would not be problematic in eastern Pennsylvania where alkalinity would probably be beneficial, and the soluble salts would leach from the soil profile rather quickly.

As shown in table 1, most of the major problems associated with reclamation of smelter-affected soils would be mitigated or solved by treatment with a sludge/fly ash mixture. The primary reasons for trying a combination of sewage sludge and fly ash are twofold. First, it was postulated that the handling characteristics of the mixture would be improved: Sludge at 15 to 20% solids can be quite sloppy when used alone, while fly ash is prone to dust generation. Second, the light color of the fly ash was thought to be beneficial for an unincorporated use, as it would lighten the dark-colored sludge, thereby helping to prevent excessive temperatures from developing at or near the soil surface. Additionally, it was felt that the fly ash, being composed of soil-sized particles, would help keep the sludge from crusting on the surface, thereby increasing the porosity, infiltration, and percolation rates of the mixture.

The use of either sludge or fly ash alone, without incorporation, would almost certainly fail in this application. The black sludge tends to dry and crust on the surface. This cracked surface repels water, which enters the cracks, moves below the sludge, and would move the sludge off the slope and off-site. Fly ash alone, without incorporation, would either dry and blow off the site or erode from the slopes during rainfall events.

GREENHOUSE STUDY

A greenhouse study was conducted from February 1986 to June 1986 as a preliminary step in determining if the application of a sewage sludge and fly ash mixture would be an effective technology for revegetating the defoliated portions of Blue Mountain. The greenhouse study was designed to evaluate the proposed amendments and to screen herbaceous species. The study was conducted at the USDA Soil Conservation Service Plant Materials Center, Corning, NY. The reader is referred to USEPA (1987) for more complete coverage of all aspects of both the greenhouse and field studies, as space is limited in this presentation.

Materials and Methods

Twelve herbaceous species were grown in containers with sludge or sludge/fly ash mixtures placed on top of contaminated soils. Open-bottomed half-gallon milk cartons were used as planting containers to facilitate removing the below-ground biomass following the study. Each container was 10 cm by 10 cm and 25 cm in height. All containers were filled with 2.5 cm of sand in the bottom, followed by 10 cm of contaminated surface soil collected from Blue Mountain. The next step was to treat all containers except the controls with the equivalent of 10 tons/acre of lime and the equivalent of 80 lb/acre K (132 lb/acre potash). The application rates for the lime and potash were determined by earlier soil tests to ascertain existing conditions. The sludge or sludge/fly ash amendments were applied next at a depth of 5 cm. Following this, the various species were seeded at a rate of 0.4 g/pot, which is equivalent to 40 lb/acre, and mulched with the equivalent of 3,000 lb/acre of cellulose fiber mulch. Greenhouse temperatures were maintained at 20-22^{o} C, supplemental 24-hour light was provided, and the study was conducted for 98 days.

Treatments consisted of five amendments and a control. Each treatment was replicated three times to provide enough biomass to conduct metals uptake analyses for both the above- and below-ground biomass. The six treatment combinations used the following mix ratios:

1) 1 Sludge (1S)
2) 1 Sludge : 1 Fly Ash (1S:1FA)
3) 2 Sludge : 1 Fly Ash (2S:1FA)
4) 3 Sludge : 1 Fly Ash (3S:1FA)
5) 3 Sludge : 1 Fly Ash [with the addition of 2.5 cm humus between the soil and the amendment (3S:1FA:H)]
6) Control (Commercial potting medium only)

The amount of sludge applied in all treatments was constant, while the fly ash varied, e.g., the 2:1 treatment contained one-half the amount of fly ash that the 1:1 treatment had. All sludge and fly ash amendments were prepared on a volume basis. The amount of sludge applied per treatment was equivalent to applying 2,000 lb/acre total organic nitrogen.

Earlier site evaluation on Blue Mountain revealed the presence of significant amounts of a black humus which appeared to be undecomposed leaves and tree bark. Subsequent laboratory analysis indicated that this humus contained the highest recorded metals values on the mountain, so Treatment 5 was added to the experiment to determine if this humus would have an adverse effect on revegetation attempts.

The sludge used for the study was obtained from the City of Allentown, PA, and the fly ash was obtained from the Pennsylvania Power and Light Co. generating station at Washingtonville, PA.

The species planted were as follows: 1)'Oahe' intermediate wheatgrass, Agropyron intermedium; 2) 'Streeker' redtop, Agrostis gigantea; 3)'Niagara' big bluestem, Andropogon gerardi; 4) tufted hairgrass (PI-314562), Deschampsia caespitosa; 5) 'KY-31' tall fescue, Festuca arundinacea; 6) common goatsrue (PI-283238), Galega officinalis; 7) 'Lathco' flatpea, Lathyrus sylvestris; 8) 'Pennfine' perennial ryegrass, Lolium perenne; 9) 'Empire' birdsfoot trefoil, Lotus corniculatus; 10) 'Blackwell' switchgrass, Panicum virgatum; 11) 'Aldous' little bluestem, Schizachyrium scoparium; and 12) kura clover (PI-T12818), Trifolium ambiguum.

Results and Discussion: Greenhouse Study

Germination and Height Growth

Eleven of the twelve species studied germinated and grew in all replications of all six treatments. The exception was common goatsrue (Galega officinalis), which did not germinate in any treatment, including the control. This is believed to be due to an extremely hard seed coat.

With few exceptions, either the 3S:1FA or the 3S:1FA:H treatment yielded the greatest heights. The exceptions were redtop (2S:1FA), and perennial ryegrass (1S). The growth differences were, for the most part, not significant among treatments and show that these species will germinate and grow on the contaminated soils of Blue Mountain when it is properly amended. The percent cover was much more uniform across treatments, with up to 100% cover appearing in each treatment, varying with the species. A vigor analysis among species and across treatments revealed that a fairly steady decrease in plant vigor is seen across species when treatments are compared. The treatments having the greatest vigor were the 3S:1FA and the 3S:1FA:H with a steady decrease down through the 1S treatment. The highly contaminated humus did not have any adverse effects for the length of this study.

Root Development

Root growth was fair to excellent across all treatments, species, and replications. Roots grew through the amendments, contaminated soil, sand, and out the bottom of the pots. The best root growth correlated with the best above-ground plant performance, as expected. The treatments with the best root growth were the 3S:1FA and 3S:1FA:H.

Total Plant Biomass

Whole-plant dry weights were determined before separating the plants into above- and below-ground portions for metals uptake analysis. Although most species did not differ significantly across treatments, the 3S:1FA:H treatment had the highest total dry plant weight in 50% of all occurrences, followed by the 3S:1FA with 25%, and finally the 2S:1FA treatment with 17% of all occurrences.

When evaluated across species, switchgrass was the highest producer of biomass, followed by tall fescue, perennial ryegrass, intermediate wheatgrass, and big bluestem. After big bluestem, there were significant drops among the grasses. Among the legumes tested, flatpea and birdsfoot trefoil were the greatest producers.

The types of grasses included in this study are both warm-season and cool-season species. The warm-season grasses, i.e., big bluestem, switchgrass, and little bluestem, usually require 1 to 3 years to become fully established on a site, but once established are extremely long-lived and tolerant of harsh site conditions. In spite of the relatively short length of the greenhouse work (98 days), the warm-season grasses performed extremely well.

Among other differences between the warm-season and cool-season grasses, several concern the use of these species in the Blue Mountain work. The cool-season species are quick to establish, but tend to have several major disadvantages. For example, the cool-season grasses do not send roots much deeper than 10 to 12 inches, while the warm-season species can extend roots from 5 to 8 feet deep on droughty sites.

In the case of Blue Mountain, the extremely high concentrations of heavy metals predominantly are chemically bound in the upper 8 to 10 inches of soil. For the cool-season species, then, most of the roots may never escape the contaminated zone, while the warm-season species may have 80% or more of their total root mass below the contaminated zone. Additionally, the warm-season grasses are much more efficient users of available moisture and nutrients.

Because of these differences in growth habits, although the cool-season grasses establish quicker, their persistence on a site this toxic as compared to the long-lived warm-season grasses needs to be monitored.

Chemical Analysis of Foliage and Roots

Foliar N for the grasses generally ran two to three times higher in the amended pots than for the control pots. N levels were fairly steady across all treatments. Birdsfoot trefoil and kura clover, both legumes, had similar N concentrations even in the control pots, which would be expected due to their N-fixation ability. Flatpea, also a legume, showed a response more typical of the grasses, which may indicate some problem with nodulation by the correct Rhizobium sp. P, K, Ca, and Mg concentrations, while variable among species, remained relatively stable across treatments. Levels of all four elements were within a normal range.

The analysis for trace metals found that the tolerance levels for agronomic crops listed in table 2, were not exceeded for Mn, Cu, Ni, and Co. Boron was below the tolerance level across all treatments except for perennial ryegrass in the 2S:1FA treatment. Cr, Al, and Fe concentrations varied widely among species and treatments, and

Table 2.--Suggested permissible tolerance levels of trace metals in agronomic crops.[a]

Element	Suggested tolerance level
	ug/g
B	100
Fe	750
Mn	300
Al	200
Zn	300
Cu	150
Cr	2
Pb	10
Co	5
Ni	50
Cd	3

[a]From Council for Agricultural Science and Technology (1976), Melsted (1973), University of Georgia Cooperative Extension Service (1979), and Adraino (1986).

were generally above tolerance levels for yield suppression of agronomic crops. Zn and Pb levels were relatively low. As expected, the levels were higher in the treatments with the humus. Only perennial ryegrass and birdsfoot trefoil exceeded the tolerance levels for both Zn and Pb. Tufted hairgrass exceeded the Pb level only, and tall fescue exceeded the Zn level only. Cd concentrations exceeded the tolerance levels in 8 of the 11 species. The only species below the tolerance level were big bluestem, little bluestem, and flatpea. Peak Cd concentrations were generally in the 3S:1FA:H treatment for all 11 species, because of the high amount of Cd in the humus.

Analyses of the roots were performed for all elements that the foliage was analyzed for, with the exception of N. Only Zn, Cd, and Pb uptake will be discussed here.

Generally, Zn, Cd, and Pb levels increased dramatically from the control pots through the various treatments. For the most part, levels rose from the controls to the 1S treatment, then decreased slightly at the 1S:1FA as a result of the liming effect of the fly ash, then once again climbed as the fly ash content decreased, finally peaking in the 3S:1FA:H mixture, due to the humus metals content.

CONCLUSIONS: Greenhouse Study

1. Of the twelve species seeded, only one, common goatsrue, Galega officinalis did not germinate, believed to be due to an extremely hard seed coat.

2. The best height growth by treatment was as follows:

- 3S:1FA -- 5 species -- big bluestem, tufted hairgrass, tall fescue, flatpea, and switchgrass.
- 3S:1FA:H -- 4 species -- intermediate wheatgrass, birdsfoot trefoil, little bluestem, and kura clover.
- 2S:1FA -- 1 species -- redtop.
- 1S -- 1 species -- perennial ryegrass.

3. All 11 surviving species grew well in the humus. Both root and shoot development appeared normal. No long-term survival data are available for plants growing on this high metal material, however.

4. Switchgrass, perennial ryegrass, and tall fescue had the best vigor ratings. The second best group of species for overall vigor were big bluestem, intermediate wheatgrass, and redtop.

5. The greatest amounts of biomass production by treatment were the 3S:1FA:H (six species); 3S:1FA (three species); and 2S:1FA (two species).

6. In general, the poorest plant performance occurred in the 1S treatment.

7. The root systems of all 11 surviving species grew through all amendments, the contaminated soil, and out the bottom of the containers.

8. Overall trace metal foliar concentrations were generally low and usually below the suggested tolerance levels for yield suppression for agronomic crops. In general, the warm-season grasses, i.e., switchgrass, big bluestem, and little bluestem accumulated much lower concentrations of foliar metals than did the cool-season grasses, i.e., redtop, tall fescue, perennial ryegrass, tufted hairgrass, and intermediate wheatgrass.

9. Trace metal concentrations in the roots were much higher than foliar levels.

10. The species that accumulated the least amounts of trace metals across all treatments was little bluestem.

11. This study demonstrated the technical feasibility of attempting to reclaim the metals-contaminated site on Blue Mountain by using this innovative reclamation technology.

Overall, the plants performing the best were switchgrass, tall fescue, intermediate wheatgrass, big bluestem, flatpea, perennial ryegrass, and birdsfoot trefoil. These species were retained for use in the field plots installed on Blue Mountain.

FIELD PLOT TRIALS

Based on the positive results in the greenhouse study, EPA approved the large-scale field plot trials on Blue Mountain. The intent of the field plot work was not only to test the soil amendments and herbaceous species, but also to test field-scale equipment. If the field work could not be completed in a cost-efficient manner using large equipment, the entire project would have to wait until equipment could be developed.

The field plots were installed by the City of Allentown's Department of Public Works. Allentown also supplied the sludge for the project. The fly ash utilized for the field plots was supplied by the Pennsylvania Power & Light Co.

Plot Layout

Ten 1-acre plots were laid out along a road bulldozed to provide access to the mid-slope portion of Blue Mountain. Three plots were located on the downslope side of the road, and the remaining seven plots were located on the uphill side of the road. The uphill plots were selected to test the spraying range of the equipment. Each 1-acre plot extended 150 ft. perpendicular to the road, and 290 ft. parallel to the road. For the herbaceous species, each plot was split into five subplots, 150 ft. deep by 58 ft. wide, for the seeding of five seed mixes. The plots were located in sets of three for application of the sludge/fly ash mixtures. Plot layout consisted of three replications of the 1S:1FA, two replications of the 2S:1FA, three replications of the 3S:1FA, one plot of a 3S:1FA mixture using sludge from the Borough of Palmerton, PA, which was very high in metals, and one plot as a control. The control plot received all amendments and seed/mulch as the other plots with the deletion of sludge and fly ash.

Application of Soil Amendments

Agricultural limestone and potash were applied to each plot using a spreader truck. Lime was applied at 10 tons/acre, and potash was applied at 132 lb/acre (80 lb/acre K). The limestone applied was approximately double the amount required to raise the soil pH to 7.0, but was used to help immobilize the large amounts of heavy metals in the soil. Next, the sludge and fly ash amendments were applied. To supply approximately 2,000 lb/acre of total organic nitrogen, an application rate of 21 dry tons sludge/acre or approximately 105 product tons/acre (20% solids) was used. The sludge amount was constant in all mixtures, as it was based on the N loading. The sludge and fly ash were mixed on a volume basis, so the amount of fly ash applied in the 1S:1FA ratio was 105 tons/acre; in the 2S:1FA ratio, the fly ash amounted to 52.5 tons/acre; and in the 3S:1FA ratio, 35 tons/acre of fly ash was used.

Initially, the sludge and flyash were mixed in the bucket of a large front-end loader, but this process was slow, and became the limiting factor in the operation. Several different methods were tried to accomplish the mixing in a more timely fashion until it became apparent that the products could be loaded into a dump truck used to ferry the amendments to the work area without mixing at all. The products were merely loaded into the dump truck, alternating layers of sludge and fly ash to achieve the desired ratio. Mixing occurred during transport to the work site, dumping, and loading into the spreader truck. The material was thrown forcibly from the rear of the spreader by a fan spinning at 12,000 to 18,000 rpm. The final products were evaluated once they had been applied, and the mix appeared to be as homogeneous by not mixing as it had been when fully mixed prior to application.

Composite samples of the sludge/fly ash mixtures were collected for chemical analysis as the amendments were applied on the plots. The actual amounts of each chemical constituent applied were close to design amounts, with the exception of Fe and Al. Concentrations of these two elements were much higher than earlier analysis had shown. Amounts of nutrients in the various mixtures ranged from 885 to 1,084 lb/acre of P, and from 2,192 to 2,705 lb/acre of N. For full soils, sludge, and fly ash chemical analyses, the reader is referred to USEPA (1987).

Hydroseeding of Grasses and Legumes

The 1-acre field plots had been subdivided into five subplots (1/5 acre each) for seeding prior to application of the amendments. The seed mixtures applied on each subplot are shown in table 3.

The plots were seeded on May 27 and 28, 1986 using a 900-gal. hydroseeder. On May 28-30, all field plots were mulched with cellulose fiber mulch at a rate of 2,000 lb/acre.

RESULTS AND DISCUSSION: Field Plot Trials

Plant Performance: 1986

Germination and emergence of most species began within 10 days following seeding. Plots were subsequently visited at 2- to 3- week intervals throughout the 1986 growing season. The earliest emergence was seen, as expected, in the cool-season grasses, i.e., tall fescue, perennial ryegrass, and intermediate wheatgrass. The next species to emerge were the warm-season grasses, switchgrass and big bluestem. Initially, there was a lack of legumes. The lack of legumes and the slower emergence of the warm-season grasses can probably be attributed to the late planting date. By the end of May, there were no more cool night temperatures to help these species break any remaining seed dormancy. Some bare areas within subplots can be attributed to "sprayer skips" by the hydroseeder.

Final data for 1986 were collected in mid-November. Data included: 1) number of plants/ft^2, 2) height, 3) vigor rating, 4) root development, and 5) tally of invading species. The method used was to construct a 3/16-inch steel cable hoop with an inside area of 1 ft^2. This hoop was then tossed randomly throughout each subplot to locate 25 sample points. All data were collected at each point.

Switchgrass had its best performance in the 1S:1FA treatment for number of plants/ft^2 and for height. The 2S:1FA ratio was intermediate, and the 3S:1FA was the worst performance.

Big bluestem, tall fescue, and birdsfoot trefoil all showed similar responses, with 1:1 best, 2:1 intermediate, and 3:1 worst. Flatpea, perennial ryegrass, and intermediate wheatgrass were not as clearly defined, but the 1:1 or 2:1 ratios were superior for either number of plants/ft^2 or height. Some of these variations can be a result of rockiness of subplots or similar environmental problems.

Root development was determined by digging one to three typical plants at each point and examining for color, amount of growth relative to shoot growth, normal development of root reserves, root hairs, and nondistorted appearance. Presence or absence of viable nodules was also checked on the roots of the legumes. In all cases, root system development was normal, unless a rock or restricting layer distorted growth.

Interestingly, there were very few to no nodules on the roots of the legumes. This may be the result of one of three possibilities: 1) the bacterial inoculant was dormant or had been heated before use, 2) the *Rhizobium* sp. did not nodulate in the presence of very high levels of N in the sludge, or 3) the levels of trace metals in the soil were so high that the *Rhizobium* sp. bacteria were killed.

The first of these three possibilities can be ruled out. The third possibility seems unlikely because the root segments in the sludge/fly ash mixtures had no more and no less nodulation than the roots in the contaminated soil. If the metals in the soil had been responsible for the lack of nodulation, there should probably be some nodules present above the soil, in the 1-1/2 to 2-inch thick layer of sludge/fly ash, unless the metals were being translocated through the roots, thereby destroying all *Rhizobium*, even those in the sludge-fly ash.

Table 3.--Species and seeding rates used on five field study subplots on Blue Mountain, PA.

Subplot #	Species	Rate(lb/acre)
1[a]	'Blackwell' switchgrass	15[c]
1[b]	'Cave-in-Rock' switchgrass	15[c]
2	'Niagara' big bluestem	30[c]
3	'Empire' birdsfoot trefoil +	20
	'Ky-31' tall fescue	40
4	'Pennfine' perennial ryegrass +	20
	'Lathco' flatpea	60
5	'Oahe' intermediate wheatgrass	30

[a]Seeded on field plots 2, 4, 6, 8, and 10.
[b]Seeded on field plats 1, 3, 5, 7, and 9.
[c]Pure live seed.

The second possibility, that the high levels of N in the sludge suppressed the Rhizobium activity is the most likely explanation. The possibility that the dormant inoculum can reside in the soil for several years until N levels decrease will need to be monitored. Possibly a top-dressing with additional inoculant will be necessary at some point in the future.

It was determined that the subjective vigor ratings were less useful than the measured ratings of plants/ft^2 and height, so vigor will not be discussed.

Plant Metals Uptake: 1986

Foliar samples only were collected in mid-November 1986 for chemical analysis. Birdsfoot trefoil and big bluestem were not collected.

N, P, K, Ca, and Mg were all within tolerable limits for all species across all sludge/fly ash ratios. Mn levels only exceeded tolerable levels in flatpea (1:1) and perennial ryegrass (1:1). All Fe levels were below the tolerable level. Cu concentrations were all well below the limit. B in all samples varied from 6 to 29% of the tolerable level.

Al uptake was varied. Switchgrass, flatpea, and perennial ryegrass exceeded the tolerable level in both the 1:1 and the 3:1 mixtures, but no adverse effects were seen on the plants. Tall fescue was under the limit in all ratios. Intermediate wheatgrass was over the limit in the 3:1 but within limits in the 1:1 ratio. Zn levels exceeded the tolerable level in all species and across all ratios except switchgrass in the 1:1 mixture. Pb was above the tolerance level in all species and all ratios. Cd was also above the tolerance level in all species and all ratios, but a definite trend developed showing the least uptake in the 1:1 plots and greater uptake in the 3:1 plots. Ni levels were all below the tolerance level. Cr levels in all species other than tall fescue slightly exceeded the tolerance level in all ratios. Finally, all Co levels were below the limit.

Many studies in the literature have shown that metals uptake by vegetation following sludge application is far greater in the first year than in subsequent years. Overall, metals uptake was not excessive, considering the site. Metals uptake should decline rapidly, but without harvest or other removal of vegetation, the metals uptake may remain higher than usual. This site will be monitored for many years in the future.

Overland Movement of Sludge/Fly Ash Mixtures

Because the amendments were not incorporated into the soil, it was anticipated that the sludge/fly ash mixtures would wash off the rocks and dead trees into the interstitial spaces to provide a growing medium. It was not anticipated that there would be any significant offsite movement. The average slopes within the plots ranged from 24 to 35%, with even steeper slopes for short distances within plots.

The sides and lower portions of each plot were examined throughout 1986 and 1987 for any evidence of overland movement. None was seen. After mixing the two materials, the handling characteristics improved greatly. The mixture is much more cohesive than either product alone. The amount of interstitial space (average 53%) was sufficient to hold the amendments on site.

One point to consider was the 1986 and 1987 precipitation. The long-term average precipitation for Palmerton, PA, is 40.5 inches. In 1986, a total of 53.02 inches was recorded, 12.52 inches above average. Only three other years have had more recorded rainfall since 1918. In 1987, two major rainfall events occurred, one in July, and one in October, both of which yielded in excess of 6.5 inches of precipitation in a short period of time. Following both of these events, several local highways were blocked with mudslides, and the access road on Blue Mountain to the plots washed out. Of significance, though, is the fact that no sludge/fly ash left the plots, even in storm events such as these. As of November 1987, there are still some standing dead trees that have had varying amounts of the sludge/fly ash mixture clinging to them since May 1986. The reader is referred to USEPA (1987) for full discussion and data for these findings.

Plant Performance: 1987

During the first week of May 1987, the field plots were visited for the first time of the growing season, and all plots other than the control had emerged remarkably well for this early in the season. Both the cool- and warm-season grasses were quite vigorous, but a noticeable lack of legumes was evident. During the 1986 growing season, the lack of legumes was attributed to the late planting date, and it was hoped that by stratifying over winter, more legumes would have germinated from the hard seed. This was not the case, however.

The plots were subsequently visited at 2- to 3-week intervals through November 1987, and no additional emergence of either birdsfoot trefoil or flatpea was noted. Both of these species compose less than 5% of the stands in the subplots where they were planted.

Final data were collected on plant performance in mid-October, 1987. Data were limited to: 1) plant height; 2) percent stand; and 3) chemical analysis of foliage samples. The rather dramatic differences in the various sludge/fly ash ratios seen in 1986 had diminished somewhat, with the 2S:1FA mixture essentially catching up with the 1S:1FA ratio. The 1987 data have not yet been published, as was the case for 1986, so (table 4) contains the mean values of the replications for each species and mixture.

As can be seen in (table 4), the 1S:1FA ratio contains four maximum values, the 2S:1FA ratio contains five maximum values, and the 3S:1FA mixture only contains one maximum value. Only the perennial ryegrass had its maximum height growth in the 3S:1FA ratio, but the percent stand was the lowest of the three ratios.

Table 4.--1987 Plant performance summary.

Species	1S:1FA ht.cm	1S:1FA %stand	2S:1FA ht.cm	2S:1FA %stand	3S:1FA ht.cm	3S:1FA %stand
	Sludge/fly ash ratio					
Switchgrass	33.1	73.7*	34.4*	60.8	26.2	42.6
Big bluestem	35.7	55.6	36.6*	55.7*	30.8	38.1
Tall fescue	32.6*	78.3	28.6	79.8*	22.7	50.0
Birdsfoot trefoil	--	--	--	--	--	--
Per. ryegrass	21.8	72.8	20.7	76.2*	23.1*	69.3
Flatpea	--	--	--	--	--	--
Inter. wheatgrass	29.4*	72.4*	26.1	65.7	18.3	56.2

*Represents greatest value for that species within that data field.

While additional work needs to be done to define the most efficient ratio, both economically and environmentally, it appears at this point that either the 1:1 or the 2:1 have the most merit from a plant growth perspective. Economically, the less fly ash that is used, the less the entire operation costs in materials and time. Additionally, since the fly ash is abrasive on the spreading equipment, the lower amount of ash prevents wear.

Concurrent with observations of plant performance made in the field plots during 1987, the return of a considerable amount of wildlife was noted within the plots. Species seen include white-tailed deer, groundhogs, white-footed mice, shrews, meadow voles, kestrels, and bluebirds. Insect life is quite abundant with a large number of spiders, crickets, grasshoppers, leaf hoppers, etc. Within the plots, decomposition of some of the dead trees has begun, indicating a return of microbial activity to this one-time biological desert.

CONCLUSIONS: Field Plot Trials

After two growing seasons, the field plots indicate that it is indeed possible to reclaim areas thought to be impossible. Extremely disturbed sites such as this with lingering toxicity problems can be revegetated, but require innovative techniques.

In September 1987, the Regional Administrator for the EPA signed a Record of Decision for the Blue Mountain project, which means that the Remedial Investigation/Feasibility Study portion of this project was concluded, and full-scale remedial action will begin. Actual work on the site will begin as soon as Remedial Design, legal negotiations, etc., are concluded. The Blue Mountain project is the largest single revegetation action ever undertaken by the EPA Superfund program, and it is intended to serve as a model of innovative technologies for other sites. One real advantage of this technology is that the financial costs of the project will be borne by the various municipalities contributing the sludge, and these municipalities are expected to accrue substantial savings over current landfill costs. This project, then addresses not only the reclamation of a toxic mountain, but also the disposal problems associated with municipal sludge and power plant fly ash.

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