VEGETATION SUCCESS, SEEPAGE, AND EROSION ON TAILING SITES RECLAIMED WITH CATTLE AND BIOSOLIDS[1]

by

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Abstract. Reclamation field studies were designed at the Phelps Dodge Morenci Mine in Arizona to evaluate the benefits of biosolids, cattle impact, and other treatment variables on soil-capped tailings. First-year monitoring has provided preliminary data about soil chemical and physical parameters, soil matric potential profiles, erosion, and vegetation measurements of ground cover, biomass production and frequency. Plots were first seeded in January 1998 with a cover crop of oats or barley. Plots were seeded again in August 1998 with native and native plus non-native plant species. Early productivity from the second seeding was inversely related to seedling density. Plots capped with unamended Gila conglomerate (Gila) materials contained meager plant nutrient levels and produced numerous small seedlings that were poorly rooted and had little standing biomass. Vegetation on the cattle and biosolids treatments was vigorous and productive but at a much lower density than unamended Gila plots. Cattle treatment added little plant-nutrient value to the Gila cap compared to biosolids amendment. However, high rates of biosolids brought excessive salinity. Straw from the cattle treatment provided an effective mulch to improve soil moisture storage but increased the potential for deep seepage. Unamended Gila and biosolids plots had intermediate moisture storage and a modest potential for seepage compared to bare tailings. Mulch cover plus a lower rate of biosolids on Gila is seen as a promising, cost-effective amendment combination for future evaluation.

Introduction

This paper presents data collected by GeoSystems Analysis, Inc. (GSA) during the first year of a tailings reclamation research program at the mine operated by Phelps Dodge Morenci, Inc. (PDMI) in southern Arizona. The program was designed to evaluate a variety of methods to establish vegetation cover on embankment tailings and measure its ability to control seepage and erosion. Tailings at PDMI are acidic and saline and contain high levels of phytotoxic metals and reduced sulfur (GSA 1997 and Lochner 1978). Successful reclamation will likely involve a soil cap that isolates plant roots from underlying tailings and an applied source of organic matter to initiate microbial activity, nutrient cycling, and sufficient vegetation cover to reduce seepage and erosion.

Earlier literature review and on-site investigations (GSA 1997) focused on determining the variability of site conditions and evaluating the potential costs and benefits of alternative tailings reclamation for tailings and tailings capped with Gila Conglomerate borrow source materials (hereafter referred to as Gila) at PDMI. Alternatives were assessed with regards to potential costs and benefits as well as meeting the regulatory requirements of the Arizona Aquifer Protection Permit (APP) Program and the Mined Land Reclamation Act (MLRA).

Based upon this earlier work, the research program focuses on six variables that will affect plant growth, seepage, and erosion on reclaimed mine tailings at PDMI: 1) the depth of Gila soil cover over tailings; 2) the type of organic matter amendment, including biosolids and cattle waste plus straw (defined as cattle impact); 3) the rate of organic matter amendment; 4) the relative success of native and native plus non-native seeded plant species; 5) a soil cover mixed with raw tailings; and 6) an unvegetated rock cover (i.e., slope armor).

This paper will primarily address comparisons between biosolids and cattle impact as organic matter sources and the effects of biosolids amendment rate. The authors are not aware of published works that compare these organic matter analogs in side-by-side replicated reclamation studies, although a great deal of anecdotal and published information exists for these sources individually, for wide-ranging site conditions and locales (Loomis, et al. 1993; Ducote 1996; Dagget 1997; Carnes 1996; Peterson and Gschwind 1972; Winkel and Roundy 1991).

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Study Methods

Plot Construction and Amendment

Four independent experiments were designed to examine different combinations of treatment variables on 5.5 acres of tailings embankment, which range from a 69- to 80-degree aspect and a 17- to 21-percent slope (Table 1). Three complete factorial experiments were conducted on a total of 54 small plots, each 24 feet wide and 40 feet long. The fourth experiment was designed as an incomplete factorial trial on 18 larger plots, each 100 feet square, or about 1/4 acre in size. Small plots allow more factors to be tested at less cost; large plots allow testing on a scale that can include cattle, reduce border effects, and better simulate large-scale heavy equipment operations.

Table 1. Experimental Design at PDMI

Cap Depth, Seed Mix and Biosolids Rate Plots

Experiment 1	12" Gila	Native + Non-native seed	0 tons/acre BS
			21 tons/acre BS
			62 tons/acre BS
		Native seed	0 tons/acre BS
			21 tons/acre BS
			62 tons/acre BS
	24" Gila	Native + Non-native seed	0 tons/acre BS
			21 tons/acre BS
			62 tons/acre BS
		Native seed	0 tons/acre BS
			21 tons/acre BS
			62 tons/acre BS

Rock Armor and Bare Tailings Plots

Experiment 2	12" Rock Cover
	Bare Tailings

Mixing Plots

Experiment 3	Biosolids at 0 dry tons/acre
	Biosolids at 21 dry tons/acre
	Biosolids at 42 dry tons/acre
	Biosolids at 63 dry tons/acre

Large Plots

Experiment 4	Bare Tailings + 800 Cattle-days
	Bare Tailings + BioFlora
	Gila Cap + 800 Cattle-days
	Gila Cap + BioFlora
	Gila Cap + 42 dry tons/acre Biosolids
	Gila Cap, Unamended

Experiment 1 is a complete factorial split-plot experiment to examine the depth of Gila cover (i.e., 12 and 24 inches), two different seed mixes (i.e., native and native plus non-native plant species), and three rates of biosolids organic amendment (i.e., 0, 21, and 63 dry tons/acre). Twelve treatments were replicated three times for a total of 36 small plots. Experiment 2 is designed to compare the effects of a 12-inch rock cover on seepage with similar plots of bare tailings. Two treatments were replicated three times for a total of six small plots. Experiment 3 is a complete factorial experiment to evaluate biosolids-amended soil covers mixed with tailings. A 9-inch Gila cap was amended with one of four rates of biosolids (i.e., 0, 21, 42, or 63 dry tons/acre) and then ripped to a total depth of 18 inches, to incorporate underlying tailings. A final 6-inch Gila cap was top-dressed over the plots. Four treatments were replicated three times for a total of 12 small plots.

The large-plot experiment (Experiment 4) was designed to examine three different organic amendments, including biosolids at 42 tons/acre, cattle impact at 800 cattle-days/acre, and a commercial organic amendment, BioFlora® (BioMega Inc., Goodyear, Arizona), on bare and Gila-capped tailings. This incomplete factorial experiment consisted of six treatments across 18 large plots.

In addition to the experimental treatment plots, reference plots were established as small plots in triplicate at two other locations. One set of reference plots was placed in an area that was capped with at least 6 feet of Gila and successfully reclaimed in 1977. Dominant vegetation includes Desert Broom (*Baccharis sarothroides*), Lehmanns Lovegrass (*Eragrostis lehmanniana* Nees) and Wilman Lovegrass (*Eragrostis superba* Peyr.). These plots are on a southern, 150-degree exposure with a slope that varies between 25 and 30 percent.

The second set of reference plots was placed on 26- to 33-percent slopes that have been undisturbed by mining activities but have a similar aspect (i.e., 10 to 57 degrees) to the experimental plots. Soils at the latter reference plots are shallow, stony, well-drained, and poorly developed members of the Graham-Lampshire-House Mountain Association (Hendricks, 1985). Species diversity at these plots is greater than on the reclaimed reference area, but dominated by grasses, especially Threeawn (*Aristida* spp.), Blue Grama (*Bouteloua gracilis*) and Fluffgrass (*Tridens pulchellus*). Catclaw

Acacia (*Acacia greggii*) and Prickly Pear (*Opuntia* sp.) cactus are common shrubs. The established vegetation of the reference plots is used to gauge revegetation success in the experimental treatments and relative responses to climate, especially drought.

Instrumentation

Seepage monitoring stations were installed in selected treatments to observe changes in soil tension gradients and pore-water chemical characteristics within a total of 39 plots. At each station suction lysimeter, Watermark® resistance block (Irrometer Co., Riverside, CA), and tensiometer instruments (Soil Measurement Systems, Tucson, AZ) were deployed at 0.5-, 1.5-, 3.0- and 6.0-foot depths, for a total of 12 instruments per station.

Erosion monitoring instruments include a pair of erosionometer transects and a sediment trap that are placed near the bottom of each of the Gila-capped plots in the large-plot experiment and on specially prepared pads of bare tailings. Installation of the erosion monitoring devices was delayed until late fall of 1998 to allow unimpeded operation of the large equipment used for seedbed preparation and seeding.

The erosionometer designed by GSA is based upon similar designs (Ranger and Frank 1978; Sanchez and Wood 1987; and Blackburn 1975). A transect is defined by two permanent stakes approximately 1.7 meters apart. A measurement rack provides a constant reference height and horizontal spacing so that measurements can be taken at 5-cm intervals along the transect as distance-to-ground surface.

A sediment trap was made from a sheet of 20-mil HDPE liner bound to a 10- by 14-foot wooden frame that is situated to collect runoff at the bottom of a plot. The total holding capacity of a sediment trap is about 350 gallons, or approximately 14 mm of runoff from the plot area directly above the trap.

Seeding

Experimental plots were seeded twice: during the winter of 1997/98 and the summer of 1998. A cover crop of oats was seeded in January and February 1998 on all of the Experiment 1 and 3 plots and on the non-cattle treatments of Experiment 4. Barley was seeded on the cattle treatments of Experiment 4. Final seeding of the plots with the experimental seed was accomplished in August 1998 after cover crop stubble was disced into the treatment surfaces with the seed mixes described in Table 2. Bare tailings plots in Experiment 4 were not re-seeded.

Data Collected

During construction and application of amendments, quality assurance/quality control checks were made to ensure adequate and uniform depth of Gila cover on experimental pads and uniform mixing of biosolids with Gila in the appropriate treatments.

Soil samples were collected in the spring of 1998 for initial characterization of treatments. Samples were composited from each sampled plot (i.e., 20 subsamples from large plots and 5 from small plots), sieved to pass a 2-mm mesh and analyzed for a variety of soil parameters,

Table 2. Seed Mixtures for PDMI Experimental Plots

Plant Species		Application Rate (PLS lbs/acre)	Origin	Seed Mix1
Acacia greggii	Catclaw Acacia	1	Native	1, 2
Aristida purpurea	Purple Three-awn	1	Native	1, 2
Atriplex canescens	Fourwing Saltbush	1	Native	1, 2
Bouteloua curtipendula	Sideoats Grama	5	Native	1, 2
Cassia covessii	Desert Senna	2	Native	1, 2
Ceratoides lanata	Winterfat	1	Native	1, 2
Eragrostis intermedia	Plains Lovegrass	5	Native	1, 2
Setaria macrostachya	Plains Bristlegrass	5	Native	1, 2
Sphaeralcea ambigua	Desert Globemallow	3	Native	1, 2
Cynodon dactylon	Common Bermudagrass	5	Non-Native	2
Eragrostis Lehmanniana	Lehmann's lovegrass	5	Non-Native	2
Panicum coloratum	Kleingrass Selection 75	5	Non-Native	2

[1]Seed Mix: 1) Native Species only, 2) Native and Non-Native Species

including texture, electrical conductivity (EC), pH, total organic carbon (TOC), and various extractable forms of N, P, K, Ca, Mg, Na, Fe, Zn, Cu, Mn, sulfate, and B.

Lysimeter samples were collected in three rounds between February 27 and August 27, 1998. Many of the first-round samples were collected from devices that had been insufficiently purged, so this round was considered preliminary. These samples were tested for EC and pH only. The second round of samples was collected on June 3, 1998, for a full suite of analyses of EC, pH, N-forms, sulfate, and total dissolved salts (TDS). The final round of samples was collected on August 20 and August 27, 1998. The analytical suite for these samples was limited to nitrogen forms, pH, and EC parameters.

Tensiometer measurements were made on 14 separate days between April 4, 1998 and January 5, 1999. The majority of measurements were made during and soon after the summer monsoon season, to capture any substantial changes in soil moisture storage in the measured profile. It should also be noted that the practical range of tensiometry is generally limited to tension ranging from saturated to about 0.7 bars. Data from the Watermark sensors was considered unreliable and was not used.

Vegetation was sampled from both the cover crop and early vegetation established from the experimental seed mixtures. Mature oats and barley samples were collected as above-ground production. Samples were clipped from randomly placed 50- by 50-cm quadrats at the rate of 20 per large plot and 5 per small plot and composited per plot. Composites were air dried to find biomass per plot.

Vegetation sampling after the second seeding was more intensive but only from the large plots. The large plots of Experiment 4 were sampled for dry shoot biomass, early germination density, frequency (i.e., when species could be identified) as well as ground cover (BLM 1996).

Results and Discussion

Soil and Pore Water Analyses

Results from the soil sample analyses show a distinct contribution of biosolids amendment and the cattle treatment to soil organic matter (i.e., as TOC) and plant macronutrients (Figure 1). The average background TOC level in Gila is about 0.19 percent compared to more than 0.5 percent in the reference plots. Adding cattle impact to Gila doubled this value to 0.46 percent. Adding

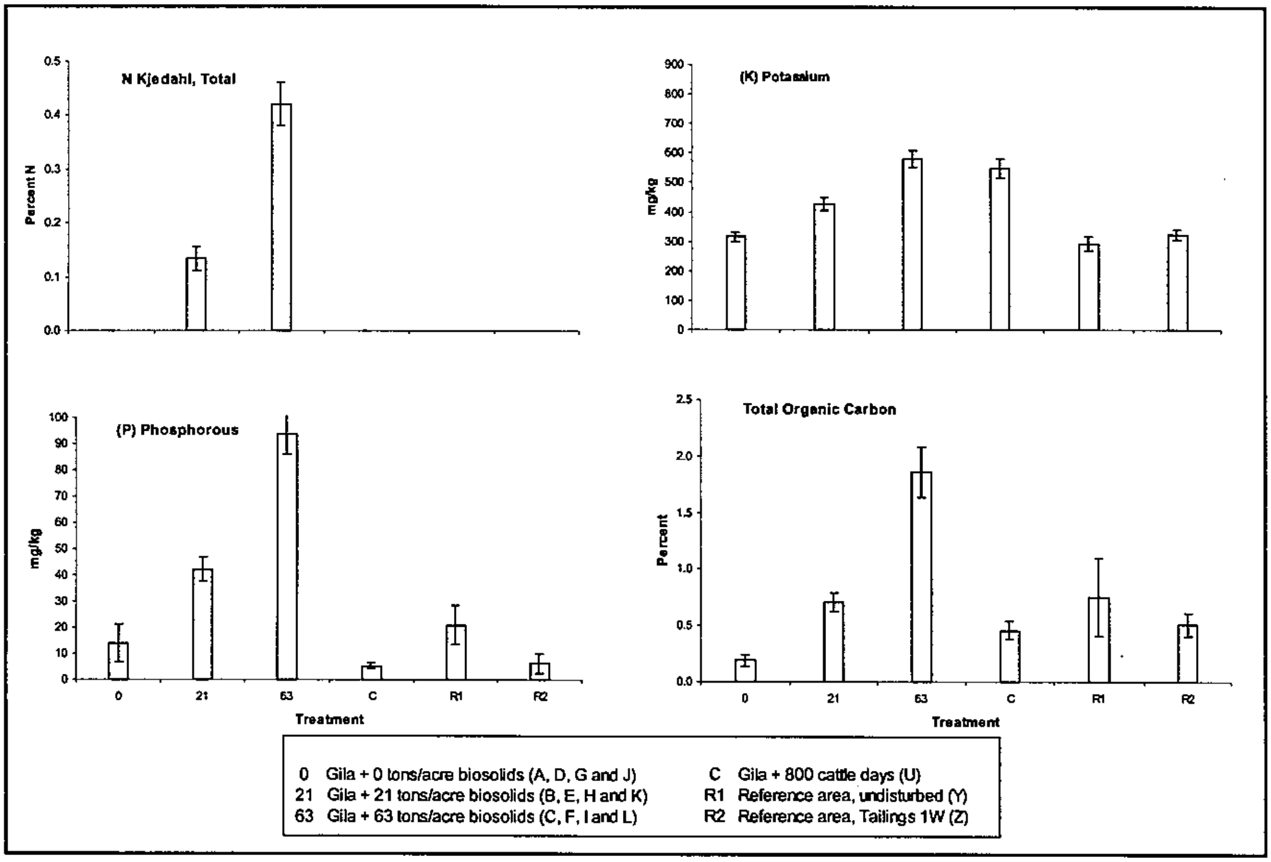

Figure 1. Macronutrients and Total Organic Carbon for Laboratory Texture Soil Samples, Initial Conditions

biosolids to Gila dramatically increased TOC: to 0.8 percent at the lowest rate of 21 tons/acre and to 1.9 percent at the highest rate of 63 tons/acre.

Although biosolids brought dramatic increases in soil organic matter and fertility to the reclamation treatments, it also brought salts. On Experiment 1 plots, 1:1 extracts from unamended Gila had an EC of approximately 1.0 dS/m. At the lowest rate of biosolids amendment (i.e., 21 tons/acre), EC increased to 6.5 dS/m; at 63 tons/acre EC increased to 10.8 dS/m.

The average EC of tailings-derived samples was above 28 dS/m. In terms of salinity alone, the tailings materials are an unsuitable plant growth medium.

Seepage

A useful graphical analysis of seepage potential is possible using tensiometer data, with the arrangement of display axes so that tension is plotted against soil depth (Figures 2 through 4). The 'zero-flux' line is added to show the 1:1 hydraulic gradient boundary between conditions that indicate net moisture movement to the soil surface, as evapotranspiration (ET), or to deep seepage. Moisture moves toward the surface when the unit decrease in soil tension per unit increase in depth is greater than one, the zero-flux line. Graphically, this is indicated by line segments that deflect clockwise relative to the zero-flux line. By contrast, seepage is indicated by line segments with a counter-clockwise deflection relative to the zero-flux line.

These analyses, while indicating the direction of moisture movement in the profile, do not indicate the rate of that movement. Moisture flux is related to the hydraulic conductivity of the material, a parameter that decreases in a non-linear fashion with increasing tension and decreasing moisture content, and varies with the type of material in question. In the case of sandy materials, such as Gila or much of the embankment tailings, hydraulic conductivity decreases dramatically with increasing tension.

In Figure 2, tension profiles are plotted for one of the large cattle-plus-Gila plots. These profiles are notable for generally having much lower soil tensions than other treatments, indicating higher moisture content. This higher moisture storage is obviously more favorable for establishing vegetation. However, the prevailing hydraulic gradients usually favor seepage. The lower tensions suggest higher hydraulic conductivity values and therefore a higher likelihood for significant deep seepage. These conditions are attributable to the mulching effects of the straw cover on the plots.

At the other extreme of tension gradients is the example of an unamended bare tailings plot (Figure 3). Except for the most shallow segments, most of the profiles indicate a net movement of moisture toward the surface, in the upper 6 feet. These data are near the measurement limit for tensiometry, so the downward gradients and extreme tension values indicated at the surface may be in error. However, given the generally sandy texture of PDMI embankment tailings materials and the relatively high tensions, any seepage in bare tailings is likely to be meager, at least as indicated during the first year of monitoring.

The unamended 12-inch Gila cap (Figure 4) presents an intermediate range of moisture potential profiles between the cattle plus Gila and bare tailings

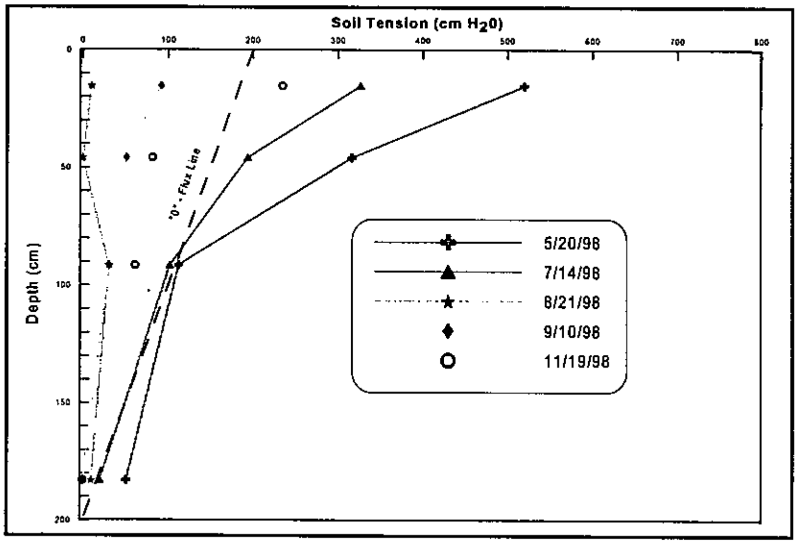

Figure 2. Soil Tension Gradients, Gila Plus Cattle

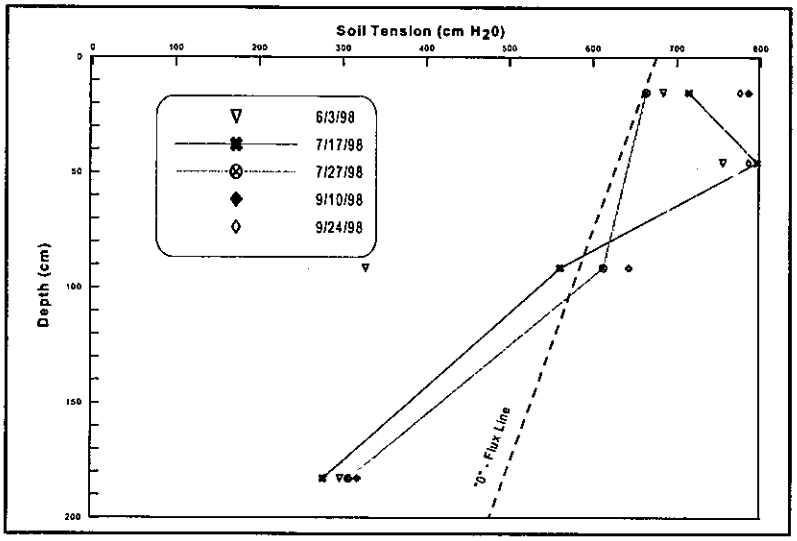

Figure 3. Soil Tension Gradients, Bare Tailings

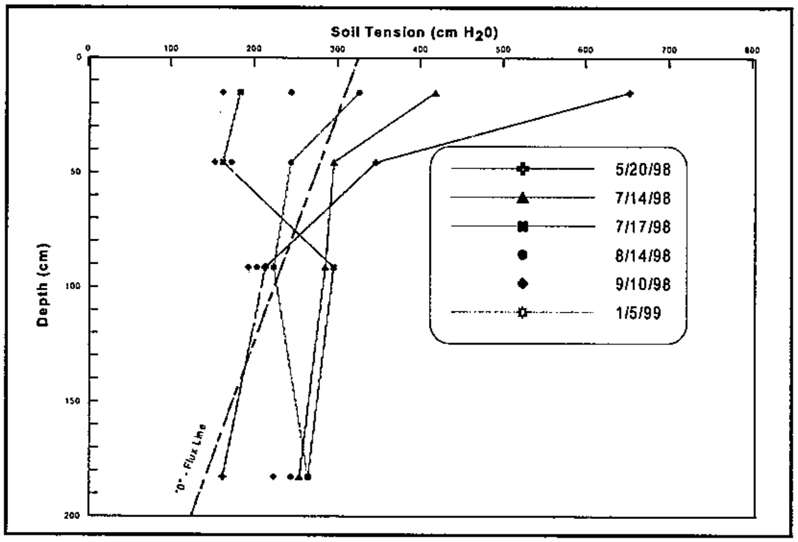

Figure 4. Soil Tension Gradients, Unamended Gila

examples. Except for the near-surface portion of the profile, these profiles represent near-unit gradient conditions and an overall tendency for gradual moisture seepage.

These examples present broad-view trends gathered from less than 1 year of measurement. The profiles will change with seasonal patterns of precipitation, potential ET at the surface, and the development of a vegetation cover. Additional tensiometer data in the coming year will increase the understanding of seepage, especially if vegetation begins to exert more of an influence on moisture storage.

Without knowing the relationship between tension and water content, an absolute soil moisture content cannot be determined. Near the end of the project, GSA will conduct tension infiltrometer tests to measure saturated hydraulic conductivity of materials at the soil surface and collect soil samples to determine soil moisture characteristic curves in the laboratory. The combination of these tests will allow the estimation of volumetric water content at various tensions (i.e., θ/φ) and the magnitude of seepage within a given soil tension profile (i.e., $K(\varphi)$). These data will be used to model estimated seepage under various reclamation treatments.

Erosion Monitoring

Since the erosion monitoring instruments placed at PDMI are a relatively recent addition, erosion data are too preliminary in nature to extrapolate for long-term trends. However, early results from erosionometers are promising (Figure 5). Measurements taken along erosionometer transects provide precise data with a resolution of measurement of approximately 1 mm. In particular, the erosion of and topographic changes within tailings materials are easily measured with this device.

Vegetation Establishment

As a growth medium for vegetation, bare tailings at PDMI are clearly hostile. Following the initial seeding of barley and oats in January 1998 on the two bare-tailings treatments, cattle plus bare tailings, and BioFlora plus bare tailings, very few seedlings emerged and expired early in the season. Consequently, these plots were not reseeded with the experimental seed mixes later in the summer.

Vegetation growth at various rates of biosolids amendment in Experiment 1 was instructive. Growth of the oats cover crop within all of the biosolids plots was initially quite lush. By comparison, oats growing on unamended Gila plots were conspicuously chlorotic, an immediate indication of nitrogen deficiency. Barley growing on large Gila plots treated with cattle impact were also chlorotic compared to oats on large plots amended with biosolids. Chlorosis was somewhat less evident in vegetation developed from the later seeding with wildland plants.

Later in the spring, the moisture level in the soil began to decrease with slackening rainfall and higher rates of plant water uptake. Leaf-burning symptoms began to appear on vegetation grown on plots with the higher biosolids rates. Oats growing in Experiment 1 plots at 63 tons/acre of biosolids suffered much more from leaf burning, an effect that was reflected in decreased productivity (Table 3).

Table 3. Oats Biomass on Small Plots

Treatment	Biomass (lb/acre)	
Unamended Gila cap	mean	281.10
	std dev	129.46
	std error	37.37
21 tons/acre biosolids	mean	601.93
	std dev	124.49
	std error	35.94
63 tons/acre biosolids	mean	416.14
	std dev	105.53
	std error	30.46

Biosolids-derived salinity is the most likely parameter of focus. For example, forage oats is considered to be a moderately salt-sensitive crop. At the highest level of soil salinity, within the 63 tons/acre of biosolids plots, where EC was almost 11 dS/m, the productivity of Bermuda grass, a species well-known to be salt-tolerant, is reduced by approximately 25 percent. Productivity of Lovegrass species is reduced by more than 50 percent (Ayers and Westcott 1989). In PDMI's climate, it is likely that salts applied as biosolids will persist in the soil.

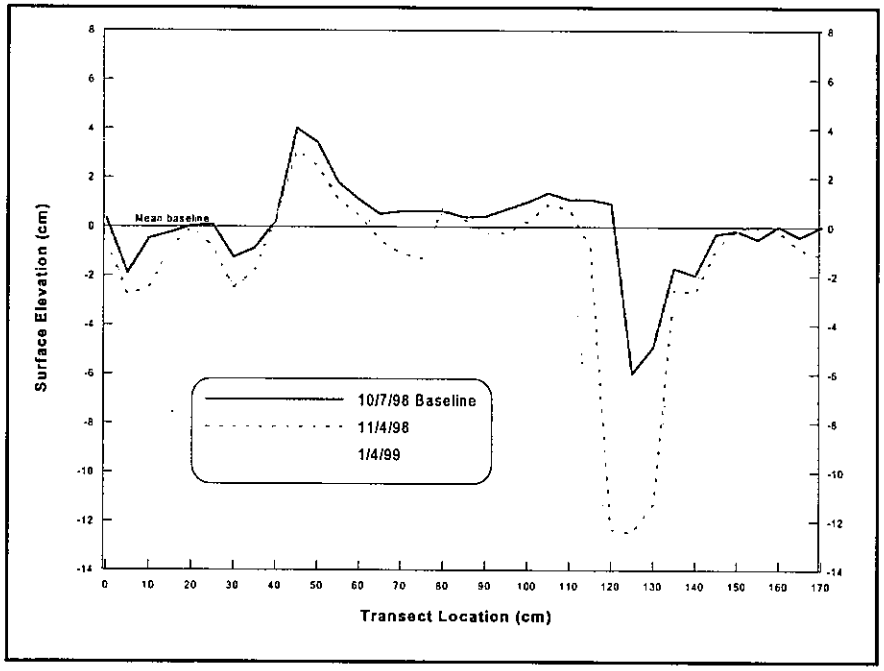

Figure 5. Topographic Changes, Erosionometer on Bare Tailings (10/7/98 to 1/4/99)

Other factors may have produced these results, such as phytotoxic levels of ammonium or a metal species not included in the analysis. However, the pattern of change in vegetation in response to rainfall events and the gradual development of symptoms with drying conditions strongly indicates salinity.

Following the second seeding, early plant establishment was measured as plant density and biomass in October (Tables 4 and 5). Density is often highly correlated with productivity in mature communities. However, in the early stages of this study the density of seedlings in the large plots tended to be inversely related to biomass.

Table 4. Seedling Density of Large Plots

Treatment	Seedlings/ acre	Seed Germination Rate
800 cattle-days	2,150,001	5.47%
BioFlora	3,390,000	8.65%
42 tons/acre biosolids	1,330,000	3.38%
Unamended Gila	3,260,000	8.30%

Table 5. Biomass on Large-Plot Experimental Seed Mix

Treatment	Biomass (lb/acre)	
800 cattle-days/acre	mean	67.20
	std dev	11.62
	std error	6.71
BioFlora	mean	12.94
	std dev	7.89
	std error	4.56
42 tons/acre biosolids	mean	96.91
	std dev	10.24
	std error	5.91
Unamended Gila	mean	12.12
	std dev	5.98
	std error	3.45

Soon after seeding, soil moisture was plentiful and high germination rates were supported. However, while more numerous, individual plants in the unamended Gila plots were much smaller, less well-rooted, and less likely to survive drought or produce viable seed. Better overall establishment, reflected in the biomass and cover data, was found in the mulched surfaces provided by the cattle treatment or where fertility was increased by biosolids.

Conclusions

While beneficial to plant establishment in terms of added moisture retention, mulching also increases the likelihood of deep seepage. On raw tailings, hydraulic gradients indicate that moisture will move toward the surface for eventual evaporation, at least to the 6-foot depth. Net downward movement of moisture on the experimental plots is likely at some depth below the monitoring instrumentation. Unamended Gila cap and Gila amended with biosolids have an intermediate effect between straw mulch and bare tailings. More incident precipitation is captured for infiltration on these surfaces than bare tailings.

The use of stored moisture by vegetation from mulched and unmulched Gila surfaces will be monitored over time as a more developed vegetation cover is established. The magnitude of seepage from different cover types will be estimated later, after tests for saturated hydraulic conductivity and soil moisture retention characteristics have been conducted.

Biosolids amendment improves plant nutrient levels and provides valuable organic matter to establish carbon cycling and microbial function. However, the early evidence suggests that introduced salinity is an important offset at higher amendment rates. In PDMI's climate, added salinity will likely persist without significant transport from slopes via runoff or unexpected leaching.

Compared to unamended Gila cap, the lower rates of biosolids have resulted in dramatic increases in site productivity. Vegetation was vigorous and well nourished. The benefits of biosolids-derived organic carbon must be evaluated in light of the eventual oxidation of applied carbon to lower, sustainable levels in the soil, and the likelihood that biosolids-derived salinity will persist.

The most significant contribution of cattle impact in the large-plot experiment was increased moisture storage. Soil fertility was improved over unamended Gila, but only marginally. Productivity on the cattle plots was similar to that of Gila with biosolids, although a greater number of plants (e.g., grasses) reached maturity and produced viable seedheads on the cattle plots.

In the large-plot experiment, the unamended Gila and Gila plus BioFlora were equivalent. BioFlora made no apparent contribution to soil fertility or site productivity. On both treatments, many seeds of the experimental seed mix had germinated but seedlings were not vigorous and were unlikely to survive drought or produce viable seed.

Early results with erosionometer transect measurements are promising. During the next year, erosion on bare tailings plots should be adequately described. Whether changes in Gila-amended plots can be resolved remains to be seen.

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