Soil Water Retention on Gold Mine Surfaces in the Mojave Desert

Lawrence R. Walker[1,2]
Elizabeth A. Powell[1]

Abstract

An experimental analysis of soil water retention was conducted on three substrates (an abandoned road, an overburden pile, and a heap leach) created by gold mining activities in the Mojave Desert in southeastern California. We mixed each substrate with straw, and the overburden pile and heap leach with growth medium, then applied surface rock mulch to half the plots in an attempt to increase soil water-holding capacity for revegetation efforts. For each of the six treatments (controls included) we monitored soil water with time domain reflectometry following both a simulation of a rainfall event and a natural rainfall that occurred immediately following the simulation. Both the simulation and the rainfall increased soil water between 3 and 8%, depending on the substrate. Water retention patterns in the two-week periods following each water addition were similar between the simulation and rainfall, and among all substrate types as values returned to background (pre-water) conditions. The abandoned road substrate had higher background water content (16.5%) than the overburden pile (6%) and heap leach (5%). The road also had three times higher organic matter and five times higher soil nitrogen than the other two sites. Soil water retention was improved on the overburden pile by the addition of just surface rock mulch or of straw-plus-rock mulch. On the heap leach, increases were found with rock mulch only or with growth medium-plus-rock mulch. Rock mulches did not improve soil water retention and straw additions decreased soil water on the abandoned road. Judicious use of soil amendments can improve soil water conditions and improve revegetation efforts on disturbed lands in desert environments.

Key words: gold mining, heap leach, Mojave Desert, mine tailings, mulching, soil water retention.

[1]Department of Biological Sciences, University of Nevada, Las Vegas, Box 454004, 4505 Maryland Parkway, Las Vegas, NV 89154–4004, U.S.A.
[2]Address correspondence to L. Walker, email walker@nevada.edu

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Introduction

Revegetation of mined surfaces is a challenging proposition because organic matter, nutrients, and water needed for plant growth are generally minimal, soil pH may be either very acidic or alkaline, and soil compaction may be severe (Chambers et al. 1987, 1994; Iverson & Wali 1992). The federal Surface Mining Control and Reclamation Act (SMCRA) of 1977 (United States Congress 1977) requires mining companies to establish a diverse and permanent vegetation capable of regeneration. The revegetated community must meet the criteria for success after five years in mesic areas and 10 years in arid areas for bond release (Gillis 1992; Chambers et al. 1994; Fidelibus et al. 1996). The criteria for success are often difficult to establish, in part because of the difficulty of comparing newly disturbed sites with much older reference sites, and the innate variability in natural ecosystems used as references (White & Walker 1997). Some important criteria used to evaluate restoration success include the ability of the community to regenerate, high functional or gamma diversity, and well-established soil microflora (Gillis 1992). Attempts to accelerate recovery of mine surfaces include additions of nutrients (Ashton et al. 1997), organic matter (e.g., with mulches; Zink & Allen 1998), shade, or by reducing soil compaction (e.g., by ripping; Ashby 1997). Plantings (especially into clusters) can facilitate entrapment of windblown debris and seeds, attract animals, and promote colonization by mycorrhizae and soil microbes (Allen et al. 1987; Chambers et al. 1994; MacMahon 1997). However, introduced plants (especially grasses) may respond more quickly to nutrients and watering and develop dense swards or thickets that inhibit further colonization by native species (Monsen & McArthur 1995; Walker 1999).

Revegetation of mine tailings in arid environments presents a particular challenge, because nutrients, microbes, plants, and animals do not begin the process of habitat amelioration without adequate soil water (Iverson & Wali 1992). Watering is not always feasible because of cost and transport issues and the promotion of surface salinization or undesirable species (Luken 1990), but some success has been obtained with infrequent, deep-root watering of transplants (Bainbridge et al. 1995; Holden & Miller 1995) or drip irrigation. Clustering of transplants or sown seeds can aid in water retention by reducing evaporative losses (from shading, trapping of snow, increasing water infiltration into the soil). However, established plants may also lower soil water availability. Physical alterations of the topography also can help, as in the creation of furrows, contouring to reduce erosion, and the use of large rocks or plastic sheets to promote condensation (Scholl & Aldon 1979; Biggins et al. 1985; Iverson & Wali 1992). Mulching with straw, rocks, or other coarse debris also reduces water loss (Voorhees 1986; Plass 1988; Walker & Powell 1999) and increases seed germination (Chambers 2000).

In order to determine the best techniques for mine revegetation efforts in arid environments, we measured soil water-holding capacity by conducting a "dry-down" experiment on three substrates resulting from mining activities in southeastern California. The experiment was repeated with a natural rainfall. We examined the influence of surface rock mulches and the addition of growth medium or straw amendments on water retention and seven other soil variables on the three mining substrates. The specific purpose of these measurements was to determine baseline soil conditions to guide revegetation efforts at the mine.

Methods

Study Site and Experimental Design

Our study was conducted at the Castle Mountain Mine, near the border of California and Nevada in the Mojave Desert (35°15′N, 115°6′W). The mine is located at an average elevation of 1,300 m. The local vegetation is a mosaic of plant communities dominated by *Coleogyne ramosissima* (blackbrush), *Larrea tridentata* (creosote bush), and *Yucca brevifolia* (Joshua tree) that is underlain by calcareous soils with low nutrient content. Mean annual precipitation is low (<200 mm) and variable; 127 mm was recorded at the mine in 1996 (Viceroy Gold Corporation 1998). Typical annual maximum and minimum temperatures at that elevation in the Mojave Desert are 35°C and −15°C, respectively (National Climatic Data Center 1996). Winters are generally cool and moist, and summers are hot and dry.

In May and June 1996, we conducted an experimental "dry-down" experiment to measure the water retention of three different substrates at Castle Mountain Mine: an abandoned road, an overburden pile, and a heap leach. The Green and Gold Road was a bulldozed dirt road (3 m wide × ca. 120 m long) that had not been used by mining activities for several years. The overburden pile was composed of highly compacted, and partly crushed rock taken from the open mine pits. We used a portion of the pile that had an approximately two-year-old surface and that was visually typical of the entire pile. We were not able to systematically assess the variability of the entire 22-ha surface due to ongoing mining activities. The heap leach was a ca. 40-m tall pile of finely crushed gold-bearing ore to which cement flocculent had been added. It had been repeatedly leached with a sodium cyanide and sodium hydroxide solution to remove the gold (Bainbridge et al. 1994). A final rinse with water was done before revegetation efforts began. The heap leach (ca. 20 ha) was much more uniform in texture than the road or the overburden pile. Our site was on a 50 × 50-m portion of the heap leach that has a surface less than one year old and that was set aside for revegetation research. In addition to monitoring soil water during the dry-down experiment, we also measured seven other soil parameters at each of the three sites: bulk density, pH, percent sand, silt and clay, organic matter, and total Kjeldahl nitrogen (see details below). We tested the effects of various soil amendments and mulches on the eight soil parameters. Only the heap leach site was a disturbance unique to gold mining. The road and overburden pile were characteristic disturbances of other surface mining activities (Leopold & Wali 1992).

At each of the three sites, plots were prepared by digging 30 × 30-cm wide by 20-cm deep holes (volume = 18 liters). Six replicates of six treatments (36 plots) were placed in completely randomized locations on a grid of points spaced 1.2 m apart and forming a 6 × 6-m square on the flat (<5° slope) surfaces of the overburden pile and heap leach. The treatments consisted of three levels of soil amendment (none, growth medium, straw) and two levels of mulch (none, surface rock mulch) for a 3 × 2 factorial design. The three soil amendments consisted of (1) a control (substrate dug up but turned over and left in place, with no added mulch); (2) addition of four liters of commercial straw (chopped and then mixed with the contents from each hole); and (3) addition of four liters of growth medium. The growth medium (the <2 mm fraction was 80% by volume with a particle density of 0.57 g/cm^3) was collected from the desert surface prior to mining and stored locally in piles (Viceroy Gold Corporation 1994). The three mulch treatments consisted of the placement of four liters of surface rock mulch (one layer of 3–8 cm diameter rocks from the overburden pile) over the top of the control, straw addition, and growth medium addition treatments. On the Green and Gold Road, six replicates of four treatments (24 plots) were placed in completely randomized locations on a grid of points spaced 1.2 m apart and forming a 1.2 m wide by 10 m long rectangle along a flat section where no previous outplanting had occurred. The four treatments on the road were the same as on the overburden pile and heap leach, except that no growth medium was added to the road substrate (control, straw addition, surface rock mulch over control, and surface rock mulch over straw addition for a 2 × 2 factorial design). We did not add growth medium to the road because soils were still present, unlike the completely altered substrates of the overburden pile and heap leach.

Soil Water

We measured soil water with time domain reflectometry (TDR; Reeves & Smith 1992) that we calibrated initially with gravimetric measurements. Two stainless steel probes were inserted vertically to a depth of 20 cm in each plot. (Although three-rod probes often get better signals, do not require a pulse transformer, and are thus better for multi-plexing, two- and three-rod probes produce similar results; Dasberg & Hopmans 1992.) On 6 May 1996, we obtained prewater soil water readings (integrated across the 20 cm) from each plot. Immediately after prewater readings were obtained, plots were watered with a sprayer with the equivalent of 19 mm (0.75 in) of rain. This amount was determined to approximate an average rainfall event from local and regional rainfall records (National Climatic Data Center 1996). Rain gauges placed in each plot were used to determine the amount of water delivered. Care was given to water the plots gently and evenly to avoid ponding and water run-off. Subsequent TDR readings were made 24 hr, 48 hr, 7 d, and 14 d after watering. Just prior to the 21 days' planned reading, a natural rain delivered 17.8 mm (0.7 in) of rain to the mine site. This was a typical storm for the area and no evidence of run-off was found after the rain. Because only 21 days had passed since the artificial watering, we expect that evaporative demand was similar for both events. TDR readings were then made 3 and 16 days after the rain. Because soil water readings were close to pre-water readings 16 days after the rain, the experiment was terminated. Data were collected as percent volumetric soil water content integrated within the entire 20 cm soil column between the two stainless steel probes (Reeves & Smith 1992).

Other Soil Parameters

We collected one soil tin (113 cm^3) from the top 4 cm of the substrate from each plot after the mulch additions were established, but before the first watering on 6 May 1996. The additional soil parameters were only analyzed for the three treatments without rock mulch (control, + straw, and + growth medium). The soils were dried to a constant mass at 40°C. Soil pH was determined on a saturation paste obtained from equal volumes of soil and water. The percentages of sand, silt, and clay were determined using the Buoyoucos hydrometer method (Day 1982). Soil organic matter was determined by mass loss upon ignition at 550°C for 4 hr (on soils that were pre-dried at 105°C for 12 hr to remove soil water; Karam 1993). A subset of soils was passed through a 0.5 mm sieve and digested in sulfuric acid, then analyzed colorimetrically for total Kjeldahl nitrogen using an automated salicylate procedure (Environmental Protection Agency 1984).

The entire contents of one 30 × 30 × 20-cm deep hole at each site were removed to estimate bulk density (mass divided by volume) by the excavation method (Blake & Hartge 1986; Page-Dumroese et al. 1999) and to calculate carbon and nitrogen pools on an areal basis. The content of each hole was sieved through a 2-mm mesh screen and particles greater than 2 mm in diameter (rock fragments) were immediately weighed and their volume determined by flotation to estimate percent volume. The volume of particles less than 2 mm in diameter (fines) was estimated by subtracting the rock fragment volume from the total pit volume. The pit volume was determined by lining each hole with plastic and filling with a measured quantity of water. The fines were then dried at 105°C before calculating bulk density (dry mass of fines/volume of fines). A second bulk density (bulk density of sieved fines) was also calculated by using the volume of fines packed into a soil tin (mass of fines/volume of tin). These two measures provide a useful indication of how much of the pit volume is occupied by large air pockets, because the first measure incorporates these, and the second measure does not. Total bulk density was calculated as the mass of rocks-plus-fines/pit volume. Although we had only one pit per habitat, a few relatively large pits can serve as useful estimates of soil characteristics at a site (Vincent & Chadwick 1994). We did not address large-scale spatial variability in soil characteristics (MacMahon 1997) because we only had one site per habitat (30 m^2 on the road, 36 m^2 on the overburden pile and the heap leach) available for sampling. Within these small sites, all soil variables except bulk density were replicated, and conclusions within each site are therefore robust. However, our recommendations for revegetation approaches should be validated with larger-scale experiments.

Statistical Analyses

Soil water was analyzed initially with repeated measures ANOVA (SigmaStat 1995), followed by one-way ANOVA for each date to determine treatment differences by applying a Bonferroni sequential adjustment of p values. Soil nutrients were analyzed with two-way ANOVA (site by treatment), followed by Tukey comparison of means. Because an unbalanced design (fewer treatments on the road) did not permit analysis of interactions, we performed two sets of ANOVAs: all three sites with shared treatments (straw addition, surface rock mulch), and just the overburden pile and heap leach with shared treatments (straw addition, growth medium addition, and surface rock mulch). All percentages were arc-sine transformed before analysis and pH was analyzed on the negative log of the hydrogen ion concentrations. Significance was determined at $p < 0.05$ (except as noted above) and means are presented with standard errors.

Results

Soil Water

Before plots were watered, the road was significantly wetter ($p < 0.001$) than the overburden pile and heap leach (Fig. 1). After watering, all three sites were significantly different from one another in percent soil water ($p < 0.001$). The road site was consistently the wettest and the heap leach was consistently the driest site. The three sites had similar rates of drying, and had all returned to near pre-water soil water levels within 2–3 wk of watering or rainfall (Fig. 1).

Control plots were significantly wetter ($p < 0.05$) than treated plots on the road prior to watering (Fig. 2A), suggesting that straw addition reduced soil water through absorption. Control plots on the road remained wetter throughout the experiment ($p < 0.05$). Control plots with rock mulch were wetter than straw addition plots on the last day of the experiment ($p < 0.01$). However, overall, rock mulch did not significantly increase soil water content on the road (Fig. 2B), and there were no significant time-by-treatment interactions, indicating the trajectories were statistically parallel.

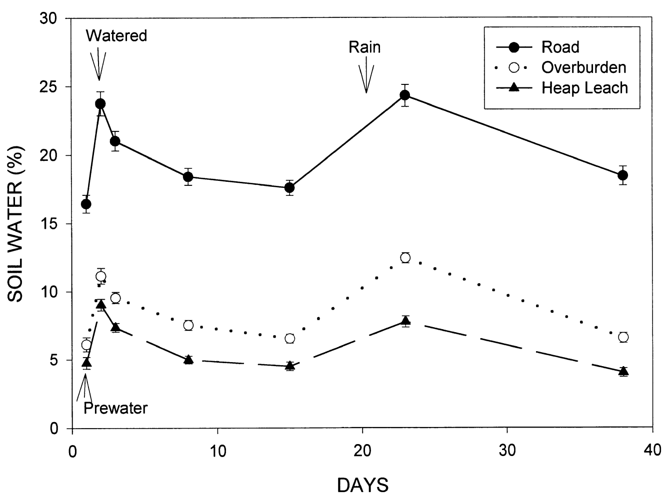

Figure 1. Percent soil water content of the three substrate types before an artificial watering and during the dry-down following the watering and a natural rain (mean ± SE, $n = 24$ plots for road and $n = 36$ for overburden pile and heap leach). All treatments were combined by substrate type.

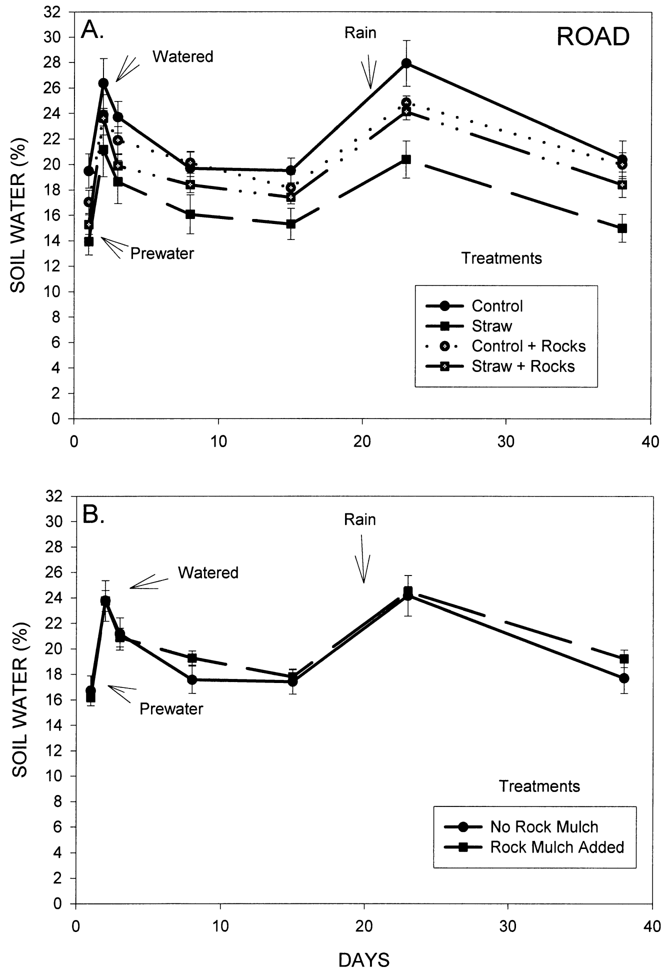

Figure 2. Percent soil water content on the road contrasting all four treatments (A) and contrasting the first two treatments in Fig. 2a without rock mulch to the last two treatments with rock mulch (B) (mean ± SE, $n = 6$ plots).

On the overburden pile, there were no significant differences among treatments before watering (Fig. 3A). After watering, the straw-plus-rock mulch treatment was significantly wetter ($p < 0.01$) than the other treatments throughout the experiment, except for the last sampling date. Rock mulch treatments (combined) were significantly wetter ($p < 0.05$) than treatments without rock mulch, except at 24 hr after watering and 3 d after the natural rain (Fig. 3B). Again, there were no time-by-treatment interactions.

On the heap leach, there were no significant differences between treatments before watering (Fig. 4A), but there were significant treatment differences after watering ($p < 0.01$). The growth medium-plus-rock mulch treatment was consistently the wettest treatment, followed by the growth medium and the control-plus-rock treatments. The straw treatment was significantly drier than all other treatments ($p < 0.01$). Rock mulch treatments combined were significantly wetter ($p < 0.05$)

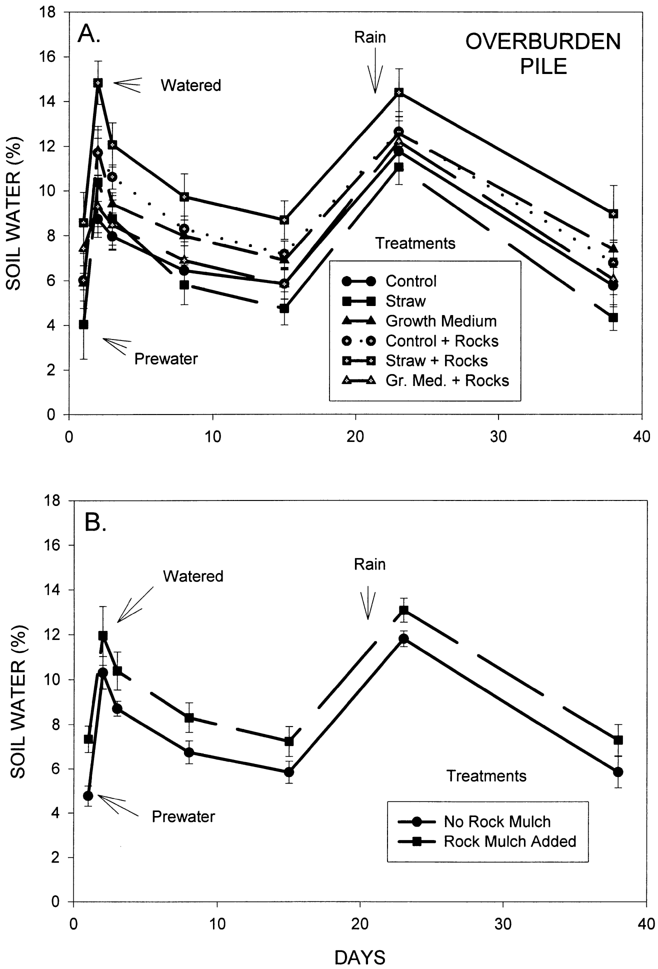

Figure 3. Percent soil water content on the overburden pile contrasting all six treatments (A) and contrasting the first three treatments in Figure 3A without rock mulch to the last three treatments with rock mulch (B) (mean ± SE, $n = 6$ plots).

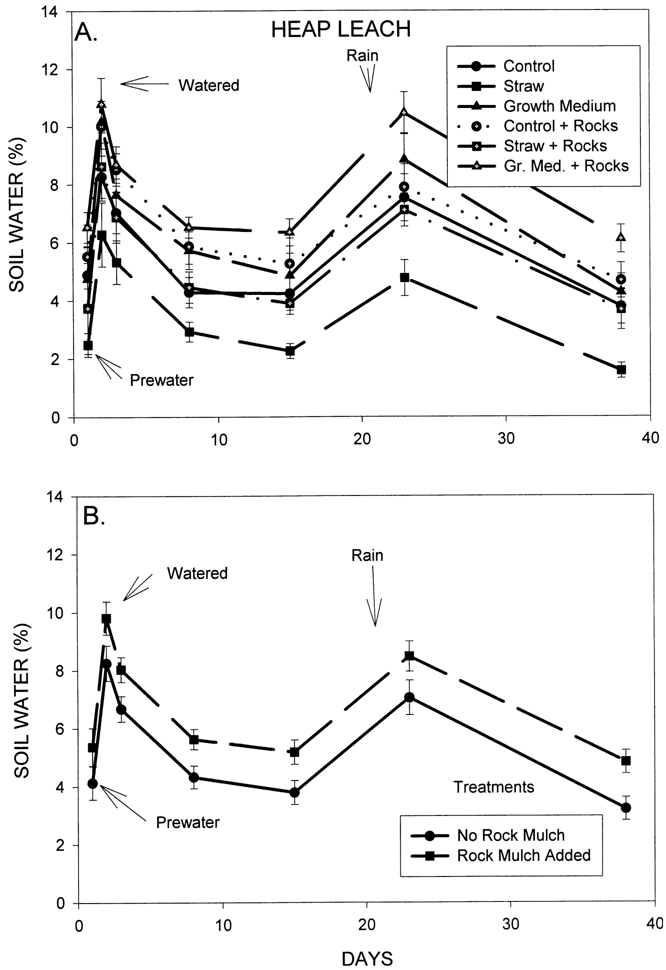

Figure 4. Percent soil water content on the heap leach contrasting all six treatments (A) and contrasting the first three treatments in Figure 4A without rock mulch to the last three treatments with rock mulch (B) (mean ± SE, $n = 6$ plots).

than treatments without rock mulch throughout the experiment, except 24 hr after watering and 3 d after the natural rain (Fig. 4B). No time-by-treatment interactions were found.

Other Soil Parameters

Soil pH (Fig. 5A) differed significantly by site ($p < 0.001$; heap leach > overburden pile > road) but straw amendments did not alter pH. However, the high pH of the heap leach was reduced by growth medium addition and the pH of the overburden pile increased ($p = 0.042$), resulting in a significant interaction ($p < 0.001$) between site and treatment when the road was removed from the analysis. All three sites had high sand content (>60%), moderately high silt content (ca. 20–40%), and very low clay content (<3% on the road and heap leach, none on the overburden pile; clay content = 100 – sand + silt). Sand ($p < 0.001$; heap leach > road > overburden pile) and silt ($p < 0.001$; overburden pile > road > heap leach) content varied by site, but not by treatment (Figs. 5B & 5C), and there were no site-by-treatment interactions. Soil organic matter was higher in the road than the overburden pile or heap leach (Fig. 5D; $p < 0.001$) and, as expected, increased in the overburden pile and heap leach with addition of growth medium ($p < 0.001$). Because straw additions decreased soil organic matter on the road but increased it at the other two sites, there was a tendency for a site-by-treatment interaction ($p = 0.091$) when growth medium addition was removed from the analysis. Total Kjeldahl nitrogen was twice as high in the road as in the overburden pile or heap leach (Fig. 5E; $p < 0.001$), and nitrogen levels were not affected by soil amendments. However, there was a site-by-treatment interaction ($p = 0.035$) with the growth medium treatment removed from the analysis, because total Kjeldahl nitrogen increased with straw addition on the overburden pile but decreased on the

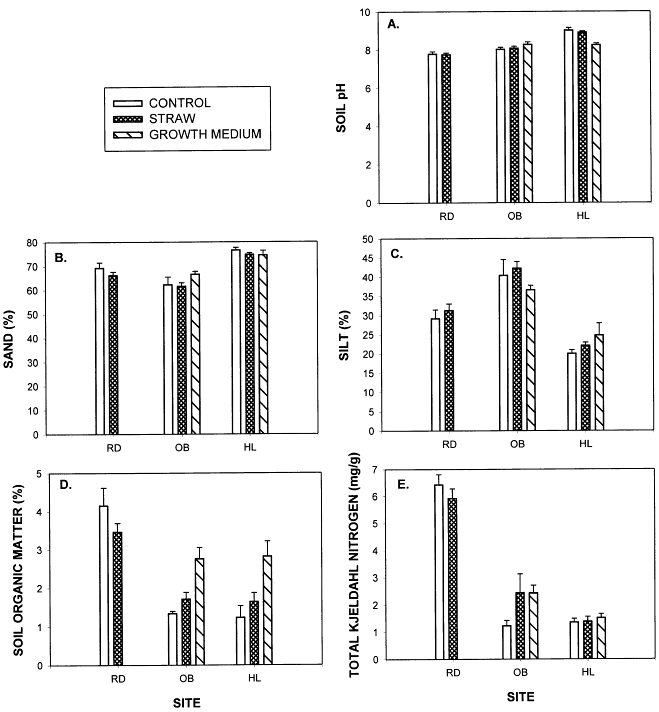

Figure 5. Soil parameters for the three substrate types (RD = road, OB = overburden, HL = heap leach) with no soil amendments (control), or additions of either straw (all three substrate types) or growth medium (added to overburden pile and heap leach only) (mean ± SE, $n = 6$ plots).

Table 1. Soil properties of three sites (RD = road, OB = overburden pile, HL = heap leach) at Castle Rock Mine. Values represent one measurement per site based on excavation of one 30 × 30 × 20 cm deep pit. Rock volume (>2 mm diameter fraction) was determined by flotation. Bulk density of fines (<2 mm diameter soil fraction) was calculated as mass of fines/volume of fines. Volume of fines was determined either as total volume minus rock volume (unsieved) or as volume of fines packed into tins of a known volume (sieved). Nitrogen (g/m^2) and organic carbon (kg/m^2) pool sizes were calculated from the product of the nutrient concentration, the soil sample depth (20 cm), the bulk density of the fines, and the volume of the fines. Organic carbon was determined by dividing soil organic matter values by 1.7.

	Site		
Soil Parameter	*RD*	*OB*	*HL*
Fines (<2 mm)			
BD (unsieved)	1.17	0.95	0.97
BD (sieved)	1.22	1.20	0.97
% vol.	46	42	39
Rocks (>2 mm)			
% vol.	54	58	61
Pool Sizes			
N (g/m^2)	69	9	11
C (kg/m^2)	2.65	0.66	0.58
Carbon/Nitrogen Ratio	38	73	51

control plots. The increases in nitrogen with both soil amendments on the overburden pile but not on the heap leach led to a tendency ($p = 0.077$) for a site-by-treatment interaction with the road removed.

The road had higher bulk density values (total and unsieved and sieved fines), nitrogen and carbon pool sizes, and a lower C:N ratio than the other two sites (Table 1). The drop in bulk density of fines from sieved to unsieved for the overburden pile reflects the presence of many large air pockets among the large rocks on the overburden pile. The heap leach substrate had no large rocks, and the two measures of bulk density of the fines were the same, reflecting the homogeneous particle size of the heap leach and high degree of compaction. The road was also highly compacted, as indicated by small differences between the two bulk density measurements. The much higher nutrient content of the road (Table 1) reflects the higher soil organic matter and nitrogen content of the fines (Fig. 5), as well as the higher proportion of fines on the road.

Discussion

Soil water availability is the most critical element for the restoration of mined surfaces in arid lands (Iverson & Wali 1992). In addition to vegetation type and cover, its availability is dependent on many other soil properties including organic matter, texture, surface roughness, bulk density, and slope. Fortunately, rather simple techniques are very effective in promoting water retention (e.g., mulches and furrows). However, these techniques may be unnecessary or even detrimental in some cases, depending on the initial substrate conditions.

In our study we had three sharply contrasting substrate types. The soils on the road were much wetter and higher in organic matter and nitrogen than the overburden pile or heap leach substrates. This suggests that the abandoned road will be the easiest area to revegetate, as demonstrated by the successful transplanting of desert shrubs and cacti already in place. Mulches and soil amendments are not necessary on the road. In fact, straw addition apparently decreased soil water, and rock mulch had no significant effect on soil water on the road. Road soils appeared to be highly compacted, so addition of fine textured soils (and/or ripping) might improve the success of revegetation activities. Compaction is an important variable affecting natural colonization of abandoned desert roads in the Mojave Desert (Bolling & Walker 2000).

Both the overburden pile and heap leach substrates need soil amendments in order to sustain vegetation. Rock mulches are a simple and effective way to maintain soil moisture between watering periods (Walker & Powell 1999), but supplemental watering, at least for the initial period of seedling or outplanting establishment, is strongly recommended for these extremely dry substrates. Initial assumptions that the heap leach was a relatively wet site, and that the overburden pile and heap leach might have relatively high nitrogen from blasting residues and cyanide, respectively, were not supported. Cyanide rapidly breaks down when exposed to oxygen or sunlight (J. Chambers 1999, personal communication) and the ammonium is volatilized (but see Cellan et al. 1999 regarding the fate of nitrates with different leaching regimes).

The overburden pile, composed of piled bedrock from the mine pit, may be the most difficult of the three substrates to revegetate. It was very low in organic matter and nitrogen content and, although compacted, probably from the heavy trucks that dumped the rock (Lockaby & Virdine 1984), also had large air pockets and large rocks. These characteristics, coupled with a relatively low volume of fines and low water-holding capacity, present special challenges for revegetation (Munshower 1994). Our values of soil pH, nitrogen, and organic matter were comparable to recently abandoned mines in North Dakota where the successional recovery of both soil properties and vegetation was projected to take more than 45 years (Iverson & Wali 1992). Bainbridge et al. (1994) had some success with *Acacia greggii* (catclaw) transplants on the overburden pile at Castle Mountain Mine, particularly when the seedlings were enclosed in protective tubes that reduced desiccation. However, growth was minimal, and after three years survival was less than 25% (L. Walker 1996, personal observation). Low soil phosphorus levels and an apparent absence of mycorrhizal fungi may have contributed to poor seedling performance as well (Bainbridge et al. 1994). The overburden pile was also an extremely dry substrate. Rock mulch in general, and straw addition plus rock mulch in particular, increased soil water levels on the overburden, and are recommended to ameliorate the harsh conditions. Straw and growth medium added important organic matter and nitrogen to the overburden, without which little vegetation could grow. Natural colonization of recent ($<$3 years old) overburden piles at Castle Mountain Mine was largely limited to one native (*Eriogonum deflexum*, skeleton weed) and one non-native (*Salsola tragus*, Russian thistle) invader (Vanier & Walker 1999).

Heap leach revegetation in arid areas is a new challenge, with few examples to follow (Denton et al. 1992; Ross 1999). In a few cases, techniques used in the recovery of overburden piles have been successful, but heap leaches generally require a different approach. The heap leach at Castle Mountain Mine had better water infiltration (lower bulk density) than the overburden pile or the road, which is typical of heap leaches in general (Ross 1999). However, the heap leach lacked the capacity for water storage of the more organic-rich road, in part because of its high sand content and low percentage of fines, and was therefore the driest of the three sites. It also lacked the large rocks and air pockets of the overburden pile. Additions of both growth medium and rock mulches increased soil water content. Straw addition decreased soil water significantly and is not recommended for use on the heap leach, despite the need to add organic matter, unless watering can continue. With an extensive array of tubing still in place, continued drip irrigation would be a possibility. Without watering, the surface of the heap leach developed a hard crust, perhaps because of the addition of the flocculent, or the upward movement of salts (Cellan et al. 1999). High pH, such as caused by the sodium hydroxide and sodium cyanide additions (pH $>$ 10), may also limit revegetation of the heap leach and necessitate thorough leaching and neutralization before plant growth can occur (Cellan et al. 1999). However, each heap leach is unique and the amount of water needed to remove toxic compounds may vary considerably (Denton et al. 1992). Bainbridge et al. (1994) found fertilizer or soil additions to the heap leach substrate at the Castle Mountain Mine increased growth of experimental plantings of *Zea mays* (corn). However, Ross (1999) discouraged the use of nitrogen fertilizers on heap leaches because it tends to favor colonization by exotic species. Similarly, additions of growth medium is helpful only when the growth medium is not too salty, acidic, or alkaline for that particular heap leach (Ross 1999).

All manipulations designed to improve revegetation have a cost. Some of the effort or cost is initial, as with transplanting onto the road, and may require little follow-through (although periodic watering of shrubs during the summer months is recommended for the first two years). Outplanting in the cooler autumn months may reduce water stress but leave the plants vulnerable to frost damage. Furrowing (already present on the heap leach) and ripping (being done to break up the surface of the road and the overburden pile) are other initial activities that require no subsequent effort and can easily be done with large machinery on a broad spatial scale. However, furrowing (as with nitrogen fertilization) may promote establishment of undesirable invasive species such as *Salsola* (Viceroy Gold Corporation 1998). Luce (1997) found water infiltration rates increased 10-fold following ripping of abandoned roads in Idaho. Rock mulch around seedbeds or transplants is more labor intensive, but probably will have important benefits on the overburden pile and heap leach substrates. Chambers (2000) found rock mulches increased soil water levels on a Wyoming overburden. Straw addition increased organic matter content in this study but may lead to initial immobilization of nutrients by soil microbes (Zink & Allen 1998). Straw addition had a drying effect on both the road and the heap leach and was useful for water retention only on the overburden pile when combined with rock mulch. Therefore, straw additions should be used in moderation.

This study provided a natural replication of an earlier artificial watering experiment, validating the techniques and results from the earlier experiment without having to simulate multiple rainfall events (Luce 1997). All three substrates had similar rates of water loss without soil amendments, but differences in loss rates were obtained by the addition of different substrates or application of surface mulches. These results confirm that the judicious use of inexpensive (or free) soil amendments or surface mulches can increase soil moisture, thereby improving revegetation of arid land mine tailings or similar habitats.

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