Mine Closure 2023 - Behrooz Abbasi, Jeff Parshley, Andy Fourie & Mark Tibbett (eds)

doi:10.36487/ACG_repo/2315_047

Successful revegetation of run-of-mine overburden soil covers without soil amendments: Copper mine closure studies in a semi-arid environment

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Abstract

Although most native plant species are well adapted to low fertility soil conditions, revegetation practitioners frequently recommend amending soil covers at considerable expense. But are soil amendments truly necessary for reclaiming semi-arid mine sites? Revegetation progress on unamended run-of-mine (ROM) overburden soil covers was monitored at three reclaimed sites for six to 12 years at two copper mines in New Mexico, USA. Monolithic, evapotranspiration (ET) soil covers (60 to 120 cm [2 to 4 ft] thick) were constructed using suitable overburden (leached cap) that was salvaged during pit development. Two sites were reclaimed using granite (GR) overburden and a third site was covered with a mixture of unmineralized rhyolite and leached granodiorite (RLG). Covers were placed over acid-generating waste and leach stockpiles. Cover construction primarily focused on material management of the ROM to reduce the rock content to approximately 50% by volume to improve seedbed conditions and water-holding capacity of the ET cover system. Both the GR and RLG soil covers are moderately coarse-textured sandy loams (USCS silty sands) with circumneutral to slightly alkaline pHs and are non-saline and non-acid generating (low sulfur). No soil amendments were used in the reclamation, though both ROM materials are considered infertile having low macronutrient (1-2 mg/kg nitrate) and organic matter content (<0.1% organic carbon). Sites were drill seeded with native seed mixes followed by mulching with long-stem grass hay. Periodic quantitative monitoring included assessment of the reclaimed site's canopy cover, shrub density and plant diversity compared to a native reference area.

Each site has progressed steadily towards meeting or exceeding the native reference area canopy cover performance standard that is used for financial assurance release. All sites experienced significant growing season drought for at least two years during establishment. Total canopy cover at one GR site was 58% in Year 6 and 64% in Year 12, exceeding the total canopy cover of the native reference area in both years. The second GR site experienced significant drought during establishment but after six growing seasons still achieved 80% reference area canopy cover standard. Vegetation of RLG covers exceeded the reference area standard within eight years following seeding. Each site also recruited numerous desirable plant species, including several native legumes and other perennial forbs. Six years after seeding, the GR sites averaged 63 additional plant species beyond the original seed mix while the RLG site had 86 volunteer species after seven years.

This work demonstrates that soil amendments are not always required to revegetate infertile ROM cover materials. Unamended overburden covers can support diverse and productive reclaimed plant communities that are resilient and capable of sustaining themselves under the adverse conditions typical of semi-arid environments.

Keywords: *overburden cover systems, run-of-mine, stockpile closure, revegetation, semi-arid reclamation*

1 Introduction

Historically, native soils and underlying alluvial materials were not salvaged and segregated as part of hard rock mine operations prior to more stringent closure regulations that have promulgated over the past 25 years. Thus, older mine operations frequently have a deficit of 'topsoil' stockpiled for cover construction at final closure. Many of these mining areas face additional challenges as the remaining undisturbed soils are thin (lithic) and do not yield sufficient quantities of borrow for use as a growth media. More recently, hard rock mines manage low sulphur materials including run-of-mine (ROM) overburden as potential reclamation cover materials to construct soil covers that isolate mine wastes and establish vegetation to support a post-mining land use (PMLU). To be considered suitable, the ROM materials need to be geochemically unreactive (i.e., low potential to generate acidity) and have textural characteristics that balances overall rock content (for erosional stability) with fine-earth (<2 mm fraction consisting of sand silt and clay particles) so the cover system holds sufficient water and supports plant growth.

The majority of research regarding the use of ROM overburden materials to construct evapotranspirative (ET) store-and-release soil covers has focused on field performance monitoring and numeric modelling related primarily to reduction of net percolation into underlying reactive mine wastes (INAP 2003, O'Kane et al. 2006; Shurniak et al. 2012; Bonstrom et al. 2012). The success of a store-and-release cover system to limit net percolation is largely reliant on the establishment and long-term functioning of a revegetated plant community appropriate for the life zone to remove soil moisture via transpiration (O'Kane & Ayers 2012; INAP 2017). Long-term cover performance thus depends on a diverse reclaimed plant community that closely resembles the existing native vegetation that surrounds the mine that can respond to the climatic variations of the region.

It is commonly assumed that reclamation using salvaged soils can ultimately achieve a plant community that mimics native vegetation and meets site-specific revegetation performance criteria: there is more uncertainty on the ability of ROM overburden to support a robust reclaimed plant community because of what might be called a 'gardening' approach to what is otherwise considered dryland reclamation. At many copper mines with porphyry copper deposits, the ROM overburden are blasted unmineralized or fully-leached lithologies above the ore body that have not been subject to near-surface weathering and/or soil development processes. As such, these ROM materials are infertile from a conventional agronomic standpoint because they have very low concentrations of organic matter and macronutrients. From the crop production or agricultural perspective, if a soil is considered infertile, standard soil chemistry parameters (pH, macronutrients [nitrogen, phosphorus, and potassium], and organic matter) are measured to determine deficiencies and develop application rates for soil amendments. Crop macronutrient requirements are often provided by agricultural testing laboratories based on the nutrient levels or can be determined using the Crop Nutrient Tool or Nutrient Tracking Tool maintained by the U.S. Department of Agriculture.

Soil science generally regards semi-arid soils as inherently infertile with low macronutrient and organic matter content. Correspondingly, semi-arid native plants have adapted to these low soil fertility conditions and are relatively unresponsive to increased soil fertility compared to crop plants (Chapin 1980). In this light, it has long been recognized that soil nitrogen deficiencies seldom limit seedling establishment on reclaimed mined land (Cook et al. 1974; Woodmansee et al. 1978; McGinnies and Crofts 1986). Ecologically, reclamation of benign overburden soil substrates is simply a process to jump-start primary succession by seeding and establishing mid-seral perennial plant species that are adapted to the surrounding life zone.

Regulatory guidance and recommendations consistently advocate for the use of soil amendments, though each jurisdiction has subtle differences in approach. In the Pacific Northwest (Washington and Oregon), it is thought that cover soils should have the same characteristics as topsoil, implying that soil organic matter needs to increase to achieve long-term success (Norman et al. 1997). The U.S. Environmental Protection Agency (EPA) promotes the use of soil amendments to initiate ecological revitalization (EPA 2007) on disturbed and contaminated landscapes. The New Mexico Mining and Minerals Division (MMD) recent reissuance of soil guidelines also begin with the premise that organic matter is 'one of the most important parameters in determining a soil's health as a medium for growing plant communities' (MMD 2022). Mine operators in New Mexico are strongly encouraged to use organic amendments (e.g., composted biosolids) at rates ranging from 38 to 224 dry Mg/ha. Conversely, agency guidance in Utah recognizes that organic amendment rates should be downward adjusted for dryland conditions (Wright 2000) while California recommends using amendments sparingly (Newton and Claassen 2003).

The addition of soil amendments can be costly. The EPA (2007) estimated, on a per hectare basis, the application of organic amendments can range from USD 10,400, to 55,800 (not adjusted for inflation) to include costs for transportation, on-site storage, application and blending operations, and specialty equipment.

Academia frequently reports on short-term control/treatment field or greenhouse experiments to evaluate organic amendments in mine reclamation (see reviews such as Garcia et al. 2017, Larney & Angers 2012). In these short-term studies, the amendment may initially improve plant production, promote soil recovery, and encourage the quick development of vegetation (Barth et al. 1988, Haering et al. 2000). It is widely understood that soil amendments in mine reclamation and land restoration can shift plant composition (Sullivan et al. 2006; Manske 2010), promote undesirable species at the expense of perennial species (Paschke et al. 2000; EPA 2007) and reduced overall plant diversity (Fresquez et al. 1990; Paschke et al. 2005; Baden et al. 2022). However, the initial benefits to plant cover or biomass with their applications may be equivocal in the long-term compared to control treatments (Bendfeldt et al. 2001, Milczarek et al. 2009, Prodgers 2009, Bay et al. 2010, Baden et al. 2022). While these longitudinal studies are uncommon, they provide evidence that amendments may not provide long-term benefits compared to unamended controls. For example, Bendfeldt and others (1999, 2001) found initial increases in soil nitrogen and organic matter with sludge applications in overburden cover soils, but after 16 years there were no lasting improvements in soil quality or annual standing biomass due to the amendment above the control treatment. With time, transgressive reductions in vegetation cover or biomass are often observed in association with application of organic or inorganic amendments (Walton et al. 2001, White et al. 1997). Biodegradation of the organic substrates to an equilibrium point in balance with the local environment most likely accounts for the loss of effectiveness over time.

The use of organic amendments in semi-arid mine land reclamation is relatively limited as a standard industry practice, particularly when conventional ‘topsoil’ resources—native soils and unconsolidated alluvium—are available as they are perceived as suitable with respect to fertility to support plant growth. When infertile ROM overburden materials are the only available cover materials for closure, revegetation practitioners, regulatory or otherwise, frequently consider amending these substrates with organic wastes (composted manure, biosolids, ‘natural’ fertilizer blends, or other industrial wastes like papermill sludge), often at considerable expense. But are soil amendments truly necessary to revegetate semi-arid mine sites when conventional topsoil resources are unavailable? To answer that question, we examine the successful revegetation of unamended ROM overburden soil covers at three sites at two copper mine operations in southwest New Mexico, USA.

2 Materials and methods

For nearly 20 years, various closure options have been evaluated for several copper mines in New Mexico that have limited topsoil resources and significant quantities of stockpiled ROM overburden (leached cap) salvaged and/or stockpiled during pit development. The materials are considered suitable as a soil substitute with respect to physical and geochemical properties. To demonstrate their ability to perform as a reclamation substrate and support vegetation, monolithic, evapotranspiration (ET) soil covers (60 to 120 cm [2 to 4 feet] thick) were constructed at two sites using Precambrian granite (GR) overburden and a third site with a mixture of unmineralized rhyolite and leached granodiorite (RLG). These site closures are part of an extensive reclamation program to close and establish a self-sustaining ecosystem, protect mine wastes from wind and water erosion and reduce the amount of water that enters a mine waste facility. The locations of these reclamation study sites are illustrated in Figure 1 and summary of the case studies follows:

- West Stockpile Test Plots (2007 to 2015)—large-scale reclamation test plots (7 ha) designed to evaluate three RLG cover thickness (nominally 60, 90 and 120 cm) on three slope configurations (top surface, 3H:1V and 2.5H:1V). Nine cover/slope configurations were evaluated, and test plots ranged in size from 0.3 to 0.6 ha.
- Copper Leach Stockpile Reclamation (2010 to present)—small stockpile closure (16 ha) with a 90 cm GR cover system over spent copper leach ore.
- USNR Sites (2015 to present)—site reclamation (9 ha) following spent ore removal with a 90 cm GR cover system. Approximately 1 ha of test plots testing different seed mixes and mulching method were seeded in 2015. The remaining 8 ha was seeded in 2016.

The elevation for the three reclaimed sites ranged from 1850 to 1950 m above sea level. The native vegetation communities in the vicinity of the study sites include the piedmont scrub savannas and mountain slope mixed evergreen woodland. Piedmont scrub savanna occurs on the gently sloping to steep pediments and fan terraces where open grassland vegetation transitions to mixed evergreen woodlands. Deeper soils tend to be dominated by gramas (*Bouteloua* spp.) and other warm-season grasses with an overstory of beargrass (*Nolina microcarpa*), broom snakeweed (*Gutierrezia sarothorae*), and catclaw mimosa (*Mimosa aculeaticapra* var. *biuncifera*). Slightly steeper slopes with shallower soils frequently have a tree overstory of Pinyon pine (*Pinus edulis*), one-seed juniper (*Juniperus monosperma*), and Emory oak (*Quercus emoryii*). With higher elevation, the scrub community transitions to mountain slope mixed evergreen woodlands on strongly sloping to very steep backslopes and ridges with shallow soils formed in residuum and colluvium. Here, relatively open stands of pinyon and ponderosa (*Pinus ponderosa*) pines as well as oaks (*Quercus* spp.) occur with a sparse understory of warm-season grasses and shrub canopy including mountain mahogany (*Cercocarpus montanus*), point-leaf manzanita (*Arctostaphylos pungens*), and beargrass.

Figure 1 Study site locations in Grant County, New Mexico

2.1 Site reclamation

Site reclamation was accomplished using available mine equipment including shovels, loaders, dozers, and haul trucks. Construction and reclamation methods at the three sites were broadly similar and included grading of subgrade mine wastes to achieve positive drainage, construction of surface water diversions and drainage channels, and placement of the ROM soil cover.

Cover materials were either directly sourced from the open pit during active mining or from previously stockpiled ROM overburden dumps. The ROM cover materials were segregated by quality control personnel who visually monitored the source materials for excessive rock and rejected materials that were too coarse with a target of 50-55% rock volume per the cover design specifications. The ROM materials were hauled using large haul trucks and staged near or on the reclamation area. Dozers and loaders managed the materials at the borrow source and/or at the reclamation site to remove the larger rock fragments and blend finer materials with excessively rocky zones during loading and placement of cover (Figure 2).

(a) (b)

Figure 2 Reduction of rock content using mine equipment at (a) the dozer push and load-out area at the borrow stockpile with oversized rock in the lower right corner; (b) excessive rock removal/management at the toe of the slope during cover placement on slopes

Following cover placement (Figure 3a), the sites were seeded with a seed mix comprised of native shrubs, grasses, and forbs. Prior to seeding, the seedbed was scarified and ripped on the contour to a depth of about 15 to 20 cm (Figure 3b). Seed was simultaneously drilled and broadcasted using a modified rangeland drill. After seeding, certified weed-free, long-stem, hay mulch was applied at a rate of 4.5 tonnes/hectare. The mulch was crimped into the cover with a tractor-drawn straight coulter disc.

(a) (b)

Figure 3 West Stockpile 3:1 sloped RLG test plot construction: (a) dozer placing cover materials dumped at the crest; (b) scarification of the cover using small rippers prior to drill seeding

2.1.1 Site and cover soil characterization

The ROM cover soils are moderately coarse-textured sandy loams (USCS silty sand) with about 50% rock volumes resulting in a low total available water (Table 1). Chemically, the ROM overburdens are circumneutral to slightly alkaline, non-saline and non-acid generating (low sulphur and sufficient neutralizing potential). Both ROM materials are considered infertile from an agricultural perspective having low nitrogen (1-2 mg/kg nitrate) and organic matter content (<0.1% organic carbon).

Table 1 Site characteristics and cover soil properties of ROM reclamation

Properties	West Stockpile test plots	Copper leach stockpile	USNR sites
ROM cover soil	unmineralized rhyolite and leached granodiorite	Precambrian granite, unmineralized and leached	
Underlying waste	acidic waste rock	acidic leached ore	acidic waste rock
USDA soil texture rock volume	Sandy Loam 49%	Sandy Loam 56%	Sandy Loam 52%
Total available water*	10.0%	8.8%	
Cover thicknesses	60, 90, & 120 cm	90 cm	90 cm
Slope geometry	Nearly level, Linear 3H:1V & 2.5H:1V Slopes	Nearly level & Linear 3H:1V Slopes	Slightly Concave 3H:1V Slopes
Fertility / chemistry			
Organic carbon	<0.1%	<0.1%	
Nitrate	1 mg/kg	2 mg/kg	
Sat. Paste pH	6.7 s.u	7.7 s.u	
Electrical conductivity	1.0 dS/m	0.5 dS/m	
Total sulfur	0.08%	0.06%	
Seeding date	2007	2010	2015 and 2016
Quant veg. monitoring	Years 5, 7, & 8**	Years 6, 11, & 12	Years 3, 5, & 6

Note: *rock corrected available water
** Year 8 vegetation monitoring grouped top surface and 3:1 sloped plots for sampling

2.2 Growing-season precipitation

The average growing-season precipitation (May through September) for the region is 253 mm (WRCC 2022). Figure 4 illustrates the departure of site growing-season precipitation relative to the regional mean for the vegetation study periods. For West Stockpile RLG test plots, growing-season precipitation is characteristic of the region with considerable variability around the mean year-over-year. The site experienced near normal to extremely wet conditions in the first four years followed by two years alternating between relatively severe drought (2011 and 2012) and wetter conditions (2013 and 2014) with the final year being dry. For the GR sites, the prevailing precipitation during the period of vegetation establishment is considered dry from a regional perspective with below average growing-season precipitation from 2017 to 2021 and severe drought in 2020 (Figure 4).

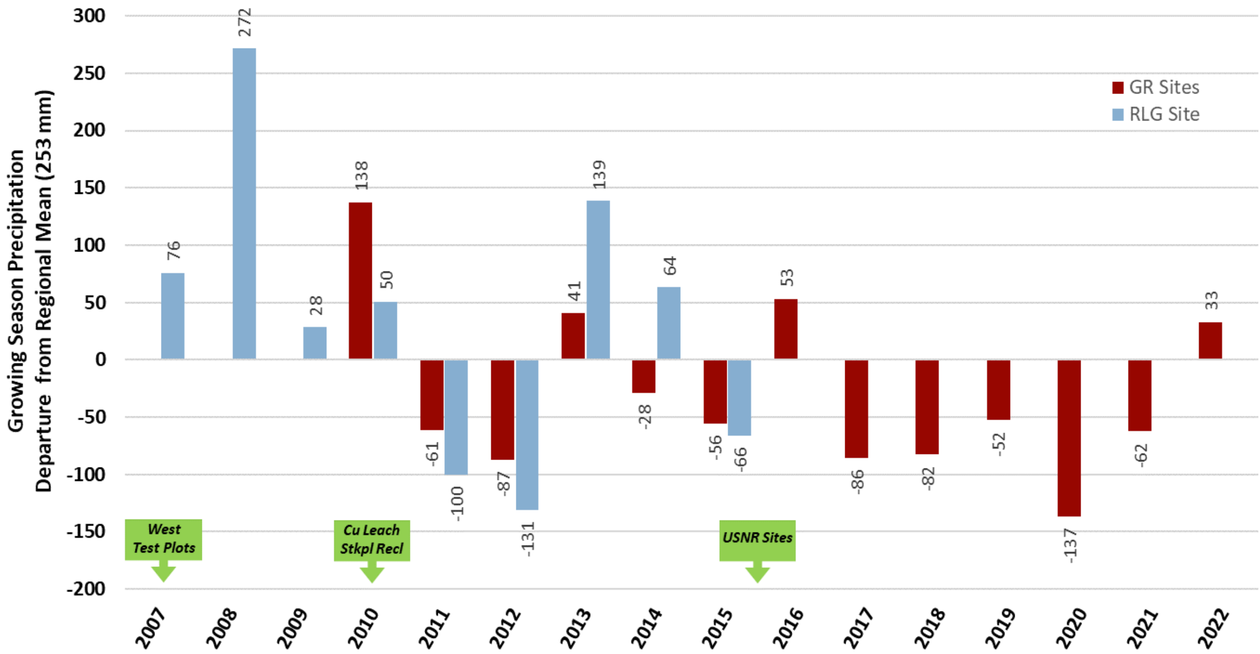


Figure 4 **Growing-season precipitation (May through September), departure from regional mean for GR and RLG sites. Seeding years for the reclaimed sites shown in green callouts**

2.3 Vegetation monitoring

A systematic sampling procedure employing a transect/quadrat system was used to select sampling plots within the reference and reclaimed areas. Randomly selected plots were sampled using four quadrats located at pre-determined intervals along a dogleg (90°) transect. Quantitative measurements were taken for each quadrat including ocular estimates of total canopy, species canopy cover, basal cover, surface litter, surface rock fragments, and bare soil. Canopy cover is defined as the percentage of quadrat area included in the vertical projection of the canopy (Daubenmire, 1968). Transect length and quadrat size varied depending on the objectives of the study and the size of area being sampled (e.g., 0.5-ha test plot versus a 16-ha reclaimed facility). Samples sizes for the studies ranged from 32 to 40 with individual quadrats considered a unique sample.

2.4 Success standards

The PMLU for the reclaimed facilities is wildlife habitat. Agency approved revegetation success standards consist of three vegetative parameters developed from native reference areas: total canopy cover, shrub density, and plant diversity. The reference areas at both sites are characterized by a grass/shrubland plant community selected during initial closure permitting of the mines in the late 1990's to represent the expected mid-seral condition of the revegetation approximately a decade following seeding. Total canopy cover in the reclamation is considered successful when it is ≥70% of the average total canopy cover of the reference area measured the same year. The success standard for shrub density is ≥60% of the shrub density of the reference area. The diversity guideline is a numeric standard and is met when warm-season perennial grasses, shrubs and non-weedy forb species meet a minimum absolute canopy cover depending on plant class. Regulations require periodic quantitative monitoring for 12 years to demonstrate the reclamation has met the performance standards and qualifies for release of financial assurance.

3 Results

3.1 West Stockpile RLG soil covers

Quantitative vegetation monitoring of the West Stockpile test plots provides strong evidence that the RLG soil covers can support a self-sustaining plant community. Figure 5 illustrates total canopy cover on different slope and cover thickness combinations for Years 5 and 7. In Year 5, plant canopy varied as a function of slope gradient more than cover thickness with all three top surface plots and the 2-ft 3:1 slope plot having equivalent or higher canopy cover than the reference area based on overlapping 90% confidence intervals.

Mean canopy cover on the 2.5:1 and 3:1 sloped test plots increased substantially in Year 7, though the top surface test plots did not differ markedly between the two monitoring events. More favourable growing-season precipitation in 2014 compared to 2012 explains the increase in canopy cover on sloped plots over the two-year period (Figure 4). Canopy cover was analysed using a one-way analysis of variance (ANOVA), followed by a Tukey's HSD post hoc test to investigate differences in canopy cover among test plots and the reference area within the sampling year. Percent canopy cover among test plots varied for each year (2012: F= 13.81, p<0.0001; 2014: F=6.17, p<0.0001). The Tukey HSD test (alpha =0.10) showed seven of the nine test plots in Year 7 had similar means compared to the reference area vegetation success standard (Figure 5). Additionally, the Year 7 (2014) canopy cover data provided no compelling evidence that increasing RLG cover thickness for a given slope geometry resulted in increased vegetation performance.

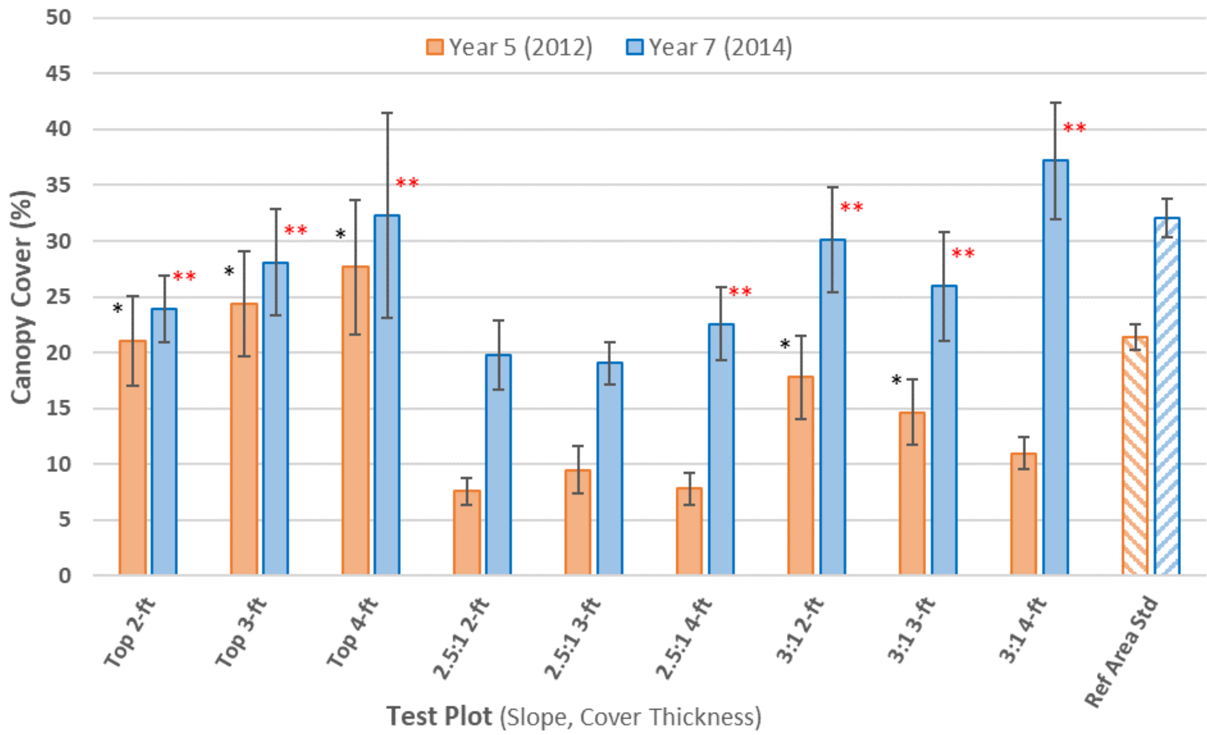


Figure 5 Years 5 and 7 canopy cover (± 90% confidence interval) on RLG soil covers for individual test plots compared to reference area standard (21.4% in Year 5 & 30.1% in Year 7). Asterisks indicate means are not significantly different across slope-cover thickness combinations and with the corresponding reference area standard using the Tukey HSD test

Year 8 vegetation monitoring at the West Stockpile sampled a combination of top surface and 3:1 sloped test plots. Due to the promulgation of regulatory closure rules for copper mines in the State of New Mexico that constrained the use of steep slopes and projected higher closure costs associated with slopes steeper than 3:1, closure planners for the mine had recently decided to minimize the use of 2.5:1 slopes in the final reclamation designs, thus monitoring these steeper plots was terminated. Mean canopy cover on the entire test plot area was 37.6%, which, under the Student's t-test (alpha =0.10), was found to be equivalent to 70%

of the reference area's canopy cover (37.4%) and meeting the minimum canopy cover requirement for vegetation success (Figure 6). Figure 7 (a & b) provides overviews of the Year 8 reclamation at the West Stockpile Test Plots top surface and 3:1 slope plots in 2015.

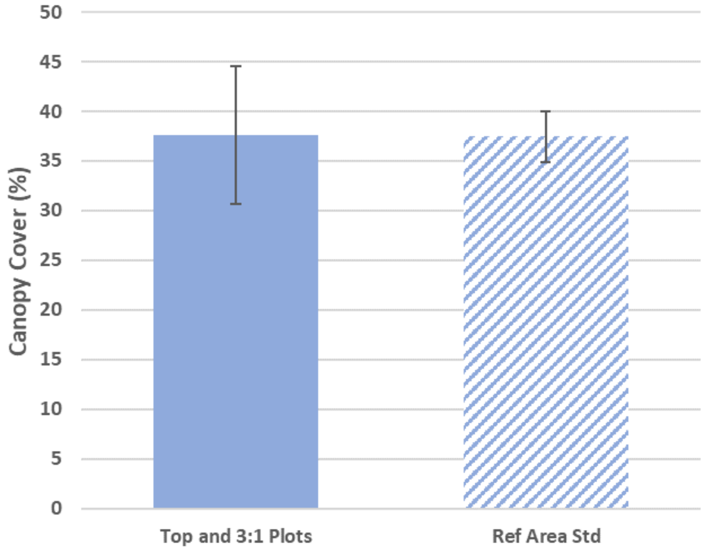
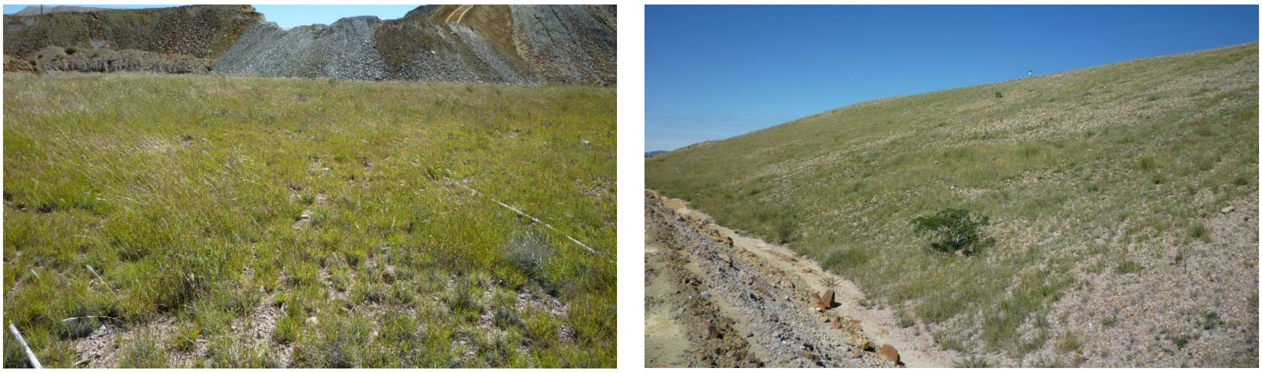


Figure 6 **Year 8 canopy cover (± 90% confidence interval) of combined top surface and 3:1 sloped West Stockpile test plots compared to the reference area standard (37.4%)**



(a) (b)

Figure 7 **Condition of reclaimed vegetation on RLG soil covers in Year 8 on (a) top surface test plots; and (b) 3:1 sloped test plots**

3.2 Copper Leach Stockpile and USNR sites with GR soil covers

Vegetation monitoring on the Copper Leach Stockpile and USNR sites provides evidence that the GR soil covers can support a self-sustaining plant community even under drought conditions (Figure 4). Figure 8 illustrates the trajectory of total canopy cover from Year 3 to Year 12 and the effects of drought. With respect to initial plant cover during the early establishment period, comparison of Year 6 results clearly demonstrates the benefit of soil moisture in the first years of plant development for the Copper Leach Stockpile as opposed to the 5 years of droughty conditions at the USNR Sites. By Year 6 on the Copper Leach Stockpile, the reclamation exceeded the reference area canopy cover standard whereas the USNR Sites hadn't quite achieved the standard. Additionally, canopy cover at the Copper Leach Stockpile declined in Year 11 (2021) following five years of drought, but the vegetation quickly responded to the above normal growing precipitation in 2022 (Year 12) to again exceed the performance standard.

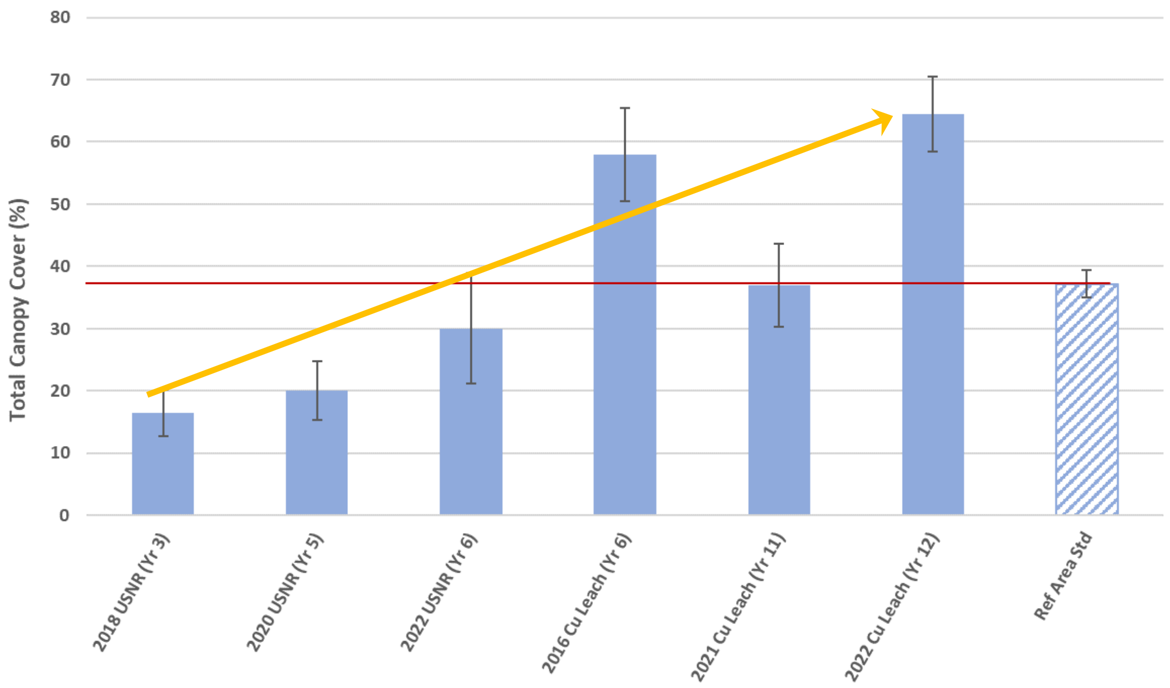


Figure 8 Progressive increase in total canopy cover (± 90% confidence interval) from Year 3 to Year 12 on GR ROM soil cover materials versus reference area standard (37.2%)

The performance of the vegetation on GR soil covers under drought conditions suggests that the reclaimed plant communities are resilient and capable of sustaining themselves under adverse conditions that are characteristic of this region. Figure 9 provides overviews of the reclamation in 2022 at the Copper Leach Stockpile (9a) and the USNR Site (9b), respectively.

(a) (b)

Figure 9 Condition of reclaimed vegetation on GR soil covers at the (a) Copper Leach Stockpile (Year 12); and (b) USNR site (Year 6)

3.3 Plant diversity and shrub density

Seeding operations and subsequent natural recruitment on the RLG and GR reclaimed sites has resulted in the establishment of a diverse shrub-grassland plant community (Table 2). The trend in vegetation composition is positive with species richness (the number of species present) increasing over time, indicating that the ROM soil covers provide suitable conditions to promote natural diversification. In a matter of 6 to 8 years, the number of observed plant species beyond the seed mix increases two times at the USNR sites to over 6-fold on the West Stockpile test plots. Plant species found in the mine's respective reference area are also provided in Table 2 to illustrate that reclaimed sites can approach equivalent species richness or alpha diversity of a native ecosystem in a short time period. The suitability of the ROM soil cover materials for sustaining vegetation is emphasized by the substantial increase in native species in the years following the initial seeding.

Vegetation composition of the reclaimed areas is characterized by the abundance of volunteer shrubs, forbs, and warm-season grasses compared to the reclamation seed mix (Table 2). Cool-season grasses are infrequently observed in the native reference areas and do not represent a significant component of the reclamation or of the species recruited from adjacent undisturbed areas. The lack of cool-season grasses is attributed to the summer monsoonal precipitation patterns for the region that favour the establishment and growth of warm-season grasses.

All sites have recruited desirable forb species, including numerous native legumes (*Dalea* and *Lotus* spp.), as well as other perennial forbs including buckwheats (*Eriogonum* spp.) and various genera of composites (*Asteraceae* family). Seeded gramas tend to dominate the warm-season grass component, yet volunteer threeawns (*Aristida* spp.), dropseeds (*Sporobolus* spp.) and bluestems (*Bothriochloa* spp.) are frequently encountered. Native shrubs also volunteer from adjacent undisturbed areas including several species of brickellbush (*Brickellia* spp.), thorny legumes (*Mimosa*, *Calliandra*, and *Acaciella* spp.) and mountain mahogany. Noxious weeds are essentially absent in reclaimed areas as the ROM overburden materials do not have a large seed bank of weedy species.

Table 2 Plant diversity and shrub density for RLG and GR reclamation and reference areas

Site	Diversity*					Shrub density (stems/m^2)
	Grasses		Forbs	Shrubs	Total	
	Warm-season	Cool-season				
RLG Soil Covers						
West Stockpile Test Plots	5 / 28	3 / 5	3 / 46	4 / 22	15 / 101	0.42
Reference area	26	2	68	16	112	0.05
GR Soil Covers						
Copper Leach Stockpile	4 / 28	4 / 2	3 / 50	4 / 18	15 / 98	2.86
USNR Sites	12 / 16	10 / 7	12 / 42	9 / 20	43 / 85	0.81
Reference area	42	3	112	43	200	1.07

Note * number of species in the reclamation seed mix / final monitoring event

All sites exceed the shrub density performance standard set at 60% of the reference area (Table 2). On GR soil covers, particularly at the Copper Leach Stockpile, the volunteer California brickellbush (*Brickellia californica*) dominates the overstory. In response, the reclamation seed mix for the USNR Sites included twice as many shrub species to narrow the available ecological niches for California brickellbush, resulting in a reduction of its occurrence.

4 Conclusion

In semi-arid environments, successful ET cover systems for hard rock mine closure balance the competing objectives of supporting vegetation, resisting erosion, and limiting net percolation. To a large degree, this is accomplished by optimizing the physical properties of the material, specifically the ratio of rock fragments to the fine-earth fraction. For soil covers constructed with chemically infertile ROM overburden materials, reclamation practitioners and regulators often assume that organic soil amendments are necessary to increase soil organic matter and macronutrient availability to ensure revegetation success despite significant costs and questionable long-term benefits.

Closure case studies using unamended ROM overburden at two copper mines in southwestern New Mexico indicate vegetation can be successfully established on ROM soil covers without soil amendments. These case studies demonstrate that in as little as six years, unamended ROM overburden materials can support a self-sustaining ecosystem that achieves a wildlife habitat PMLU by meeting or exceeding revegetation success standards for canopy cover and shrub density. These ROM soil covers are also capable of recruiting significant numbers of desirable native plant species from adjacent undisturbed areas to create a diverse reclaimed vegetation community, even under extreme drought conditions that typify semi-arid climatic regimes.

While specific site conditions should always be considered when developing a revegetation strategy for final mine closure, this work demonstrates that organic amendments are not necessary to revegetate infertile ROM cover materials. Soil amendments to increase macronutrient availability are often unnecessary for semi-arid native plant species that are adapted to harsh conditions, especially infertile, rocky soils and growing-season drought. In semi-arid environments, the amount and distribution of precipitation are probably more important determinants for vegetation establishment and performance than soil fertility. For New Mexico, unamended covers from ROM overburden are suitable as a reclamation substrate when material handling procedures reduce volumetric rock content to approximately 50 to 55% and fine-earth fraction is moderately coarse-textured. This textural combination results in a soil cover that promotes infiltration, allows the soil surface to 'self-armour' with rock to resist excessive erosion, and holds sufficient water in the root zone to support plants. This work with unamended ROM overburden for soil covers demonstrates these materials can support diverse and productive reclaimed plant communities that are resilient and capable of sustaining themselves under the adverse conditions typical of a semi-arid environment.

Acknowledgement

The authors wish to thank the many scientists, engineers, quality control technicians, and equipment operators who safely worked to build and monitor these reclaimed sites over the past 15 years.

References

Baden, S, Paschke, M & Jonas, J 2022, 'Assessment of Biodiversity, Aboveground Biomass, and Plant Cover Following Sub Alpine Mine Reclamation' In: *Proc. High Altitude Revegetation Conference*, Soc of Ecol Restoration. April 12-14 2022.

Barth, RC, Keammerer, WR & Brown, LF 1988, 'Revegetation techniques for toxic tailings', In: *Proc. High Altitude Revegetation Conference No. 8.* Soc of Ecol Restoration. Fort Collins, Colorado.

Bay, R, Carlson, K & Erickson, W 2010, 'Overburden revegetation with low seeding rates and minimal soil amendments at Tijeras Limestone quarry, NM', In *Proc. High Altitude Revegetation Conference,* Soc of Ecol Restoration.19: 147-175.

Bendfeldt, ES, Burger, JA, Daniels, WL & Feldhake, CM 1999, 'Dynamics and characterization of soil organic matter in mine soils sixteen years after amendment with native soil, sawdust and sludge', Virginia Polytechnic Inst. and State Univ., Blacksburg, VA (US).

Bendfeldt, ES, Burger, JA & Daniels, WL 2001, 'Quality of amended mine soils after sixteen years', *Soil Sci. Soc. Amer. J*. 65:1736–1744

Bonstrom, K, Allen, G O'Kane, M & Christensen, D 2012, 'Evolution of cover system design and waste rock management at a mine in the Pilbara region of Western Australia' *Proceedings of the 7th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 1-13.

Chapin, FS 1980, 'The Mineral Nutrition of Wild Plants', *Ann. Rev. Ecol. Syst.,* 11:233-260.

Cook, CW, Hyde, RM & Sims, PL 1974, 'Revegetation guidelines for surface mined areas', *Science Series No. 16.* Range Science Dep., Colorado State Univ., Fort Collins.

Daubenmire, R 1968, *Plant communities: A textbook of plant synecology*, Harper & Row, Publishers, New York.

Ebelhar, MW, Barnhisel, RI, Akin, GW, & Powell, JL 1982, 'Effect of lime, N, P and K amendments to surface-mined coal spoils on yield and chemical composition of common bermudagrass', *Reclamation and Revegetation Research* 1:327-336.

Fresquez, PR, Francis, RE & Dennis GL 1990. Soil and vegetation responses to sewage sludge on a degraded semiarid broom snakeweed/blue grama plant community. *J. Range Manage.* 43: 325-331.

Garcia, C, Hernandez, T, Coll, MD & Ondoño, S 2017, 'Organic amendments for soil restoration in arid and semiarid areas: a review', *AIMS Environmental Science,* 4(5): 640-676.

Haering, K, Daniels, W & Feagley, S 2000, 'Reclaiming mined lands with biosolids, manures, and papermill sludges', in R Barnhisel, R Darmody & W Daniels (eds.) *Reclamation of Drastically Disturbed Lands*. American Society of Agronomy. Madison, WI. pp. 615-644.

International Network for Acid Prevention (INAP), 2003, '*Evaluation of the long-term performance of dry cover systems, final report'*, Prepared by O'Kane Consultants Inc., Report No. 684-02, March.

INAP, 2017, 'Global cover system design technical guidance document', November 2017.

Larney, FJ & Angers, DA 2012, 'The role of organic amendments in soil reclamation: A review', *Canadian J. of Soil Science,* 92:19-38.

Manske, LL 2010, 'Long-term plant species shift caused by nitrogen fertilization of native rangeland', *Summary Range Research Report DREC 10-3055*. NDSU Dickinson Research Extension Center. Dickinson, ND, 16p.

McGinnies, WJ & Crofts, KA 1986, 'Effects of N and P Fertilizer Placement on Establishment of Seeded Species on Redistributed Mine Topsoil', *J. Range Mgmt,* 39:118-121.

Milczarek, M, Buchanan, M, Keller, J, Yao, T, Word, W & Steward, M 2009' 'Ten Years of Tailings Reclamation Experiments at the Morenci Mine', In the *8th International Conference on Acid Rock Drainage*, Skellefteå, Sweden.

New Mexico Mining and Minerals Division (MMD), 2022, *Guidance for Soil and Cover Material Handling and Suitability for Part 5 Existing Mines*, December 2022, https://www.emnrd.nm.gov/mmd/wp-content/uploads/sites/5/2022-1219-MMD-MARP-Soils-Guidance-FINAL.pdf.

Newton, GA & Claassen, VP 2003, *Rehabilitation of disturbed lands in California: a manual for decision-making*, California Department of Conservation, California Geological Survey. 240 p.

Norman, DK, Wampler, PJ, Throop, AH, Schnitzer, EF, & Roloff, JM 1997, *Best management practices for reclaiming surface mines in Washington and Oregon*, Washington State Department of Natural Resources.

O'Kane, MA, Meiers, G & McCombe, C 2006, 'Design, construction and performance monitoring of the large-scale waste rock cover system field trials at the historic Mount Morgan Mine Site in Queensland, Australia', *Proceedings of the First International Seminar on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 427-440.

O'Kane, MA & Ayers, B 2012, 'Cover systems that utilise the moisture store-and-release concept – do they work and how can we improve their design and performance?' *Proceedings of the 7th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 407-416.

Paschke, MW, McLendon, T & Redente, EF 2000, 'Nitrogen availability and old-field succession in a shortgrass steppe', *Ecosystems,* 3:144–158.

Paschke, MW, Topper, K Brobst, RB & Redente, EF 2005, 'Long-term effects of biosolids on revegetation of disturbed sagebrush steppe in northwestern Colorado', *Restoration Ecol.* 13: 545-551.

Prodgers, RA 2009, 'Nothing but Borrow–Revegetation Without Topsoil', *Proc of American Society of Mining and Reclamation*, Billings, MT May 30 – June 5, 2009. pp. 996-1014.

Shurniak, RE, O'Kane, MA, & Green, R 2012, 'Simulation of seven years of field performance monitoring at Rio Tinto Iron Ore, Mount Tom Price Mine using soil-plant-atmosphere numerical modelling*', Proceedings of the 7th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 393-406

Sullivan, TS, Stromberger, ME & Paschke, MW 2006, 'Parallel shifts in plant and soil microbial communities in response to biosolids in a semi-arid grassland', *Soil Biol. Biochem*. 38: 449-459.

U.S. Environmental Protection Agency (EPA) 2007, *The Use of Soil Amendments for Remediation, Revitalization and Reuse,* Solid Waste and Emergency Response. EPA 542-R-07-013 https://www.epa.gov/biosolids/use-soil-amendments-remediation-revitalization-and-reuse.

Walton, M, Herrick, JE, Gibbens, RP & Remmenga, MD 2001, 'Persistence of Municipal Biosolids in a Chihuahuan Desert Rangeland 18 Years After Application', *Arid Land Research and Management*, 15:223-232.

White, CS, Loftin, SR & Aguilar, R 1997, 'Application of biosolids to degraded semiarid rangeland: nine-year responses' *J. Environ. Qual,* 26:1663-1671

Woodmansee, RG, Reeder, JD & Berg, WA 1978, 'Nitrogen in drastically disturbed lands. In: CT Youngberg (ed) *Forest Soils and Land Use.* Dep. Forest and Wood Sci., Colorado State Univ., Fort Collins. pp 376-392.

Western Regional Climate Center (WRCC) 2022, Ft. Bayard, New Mexico Period of Record Monthly Climate Summary [database]. Retrieved 15 March 2022, https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm3265

Wright, MA 2000, *The practical guide to reclamation in Utah*, Utah Oil and Gas Mining.