EFFECT OF MECHANICAL AND BIOLOGICAL ENHANCEMENTS ON EROSION AT HIGH ELEVATION DISTURBED LANDS[1]

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Abstract. The objective of this study was to evaluate erosion control measures on sediment yields on reclaimed steep slopes and compare measured sediment yields to values predicted by Revised Universal Soil Loss Equation (RUSLE) Version 1.06. Plots were constructed on a 25 % uniform slope waste rock area. Five treatments were replicated three times in a completely randomized design. Treatments applied were no coversoil, 30 cm coversoil, 30 cm coversoil/pitting of the soil surface, 30 cm coversoil/tree slash barriers, and 30 cm of coversoil/vesicular-arbuscular mycorrhizal (AM) fungi inoculum.

Pitting was potentially an effective erosion control practice. AM inoculation did not enhance aboveground plant growth. Plant growth was lower on the no coversoil treatment. RUSLE's ability to predict sediment yields were improved by applying rill formation factor constants. The sediment-delivery ratio was 0.14 for the Coversoil/Pitting treatment and 0.60 for the Coversoil/Slash Barriers.

Additional Key Words: Steep slope reclamation, erosion control, sediment yield, RUSLE, pitting, vesicular-arbuscular mycorrhizal fungi, slash barriers, rill formation factor, sediment-delivery ratio

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Introduction

An integral part of land reclamation Best Management Plans (BMPs) is a combination of management and structural practices to control erosion hazards resulting from soil disturbance. BMPs can include erosion control activities such as increasing surface roughness of the soil, mulch incorporation, and terraces [1]. These mechanical erosion control measures are routinely used on many mined lands and construction sites to provide short-term and long-term stability to disturbed areas and minimize or eliminate off-site impacts [1].

Erosion hazards increase when vegetative cover is lost, soil permeability is low, and the ground increasingly slopes, especially if soils are shallow [2]. Good vegetative cover ideally reduces erosion hazards, but the development of adequate plant cover may be difficult due to the short growing season, an often thin, nutrient-poor, rocky soil resource, and mining practices. At higher elevations, soil erosion is dominated by spring precipitation or runoff events including snowmelt, rain on snow, and thawing soils. Soils are particularly susceptible to erosion when the frost layer recedes below surface during spring thaw. The frost layer still prevents water infiltration and generates runoff but leaves the thawed layer vulnerable to detachment and soil loss, which directly affects vegetative establishment especially during initial years after reclamation begins [1].

Kapolka and Dollhopf (2001) calculated a rill formation factor using nonlinear variable estimation [3]. An adjusted soil erodibility factor (K1) is calculated by multiplying the RUSLE estimated K value by a rill formation factor (F Factor) to obtain an optimized soil erodibility factor, K1. The F Factor is 1.0 if slopes have stable to slight rilling, 8.4 for slight to moderate rilling, and 16.6 for moderate to critical rill severity. K1 is then multiplied by the other RUSLE generated factors on a spreadsheet to obtain the optimized sediment yield value.

The objectives of this study were i) to evaluate the effectiveness of two mechanical control measures in decreasing runoff volume and sediment yield from coversoil erosion and the effect of these mechanical measures on plant growth, ii) to determine the effectiveness of biological measures in enhancing plant growth and thereby decreasing runoff volume and sediment yield from coversoil erosion, and iii) to determine the effect of coversoil depth (0 cm and 30 cm) on plant growth, and to evaluate how coversoil affects runoff volume and sediment yield.

Methodology

The Treasure Mine open pit talc mine is located in southwestern Montana approximately 24 kilometers northeast of Dillon, Montana, in the Ruby Mountain Range (Fig. 1). Native vegetation is sagebrush grassland on south facing slopes and lodgepole pine/Douglas fir on slopes facing north. Elevation is approximately 2590 meters. Average annual precipitation, based on 20 years of record, is 26.0 cm. Average yearly maximum temperature is 14.8° C, minimum temperature is –1.3° C, with 95 freeze-free days per year [4].

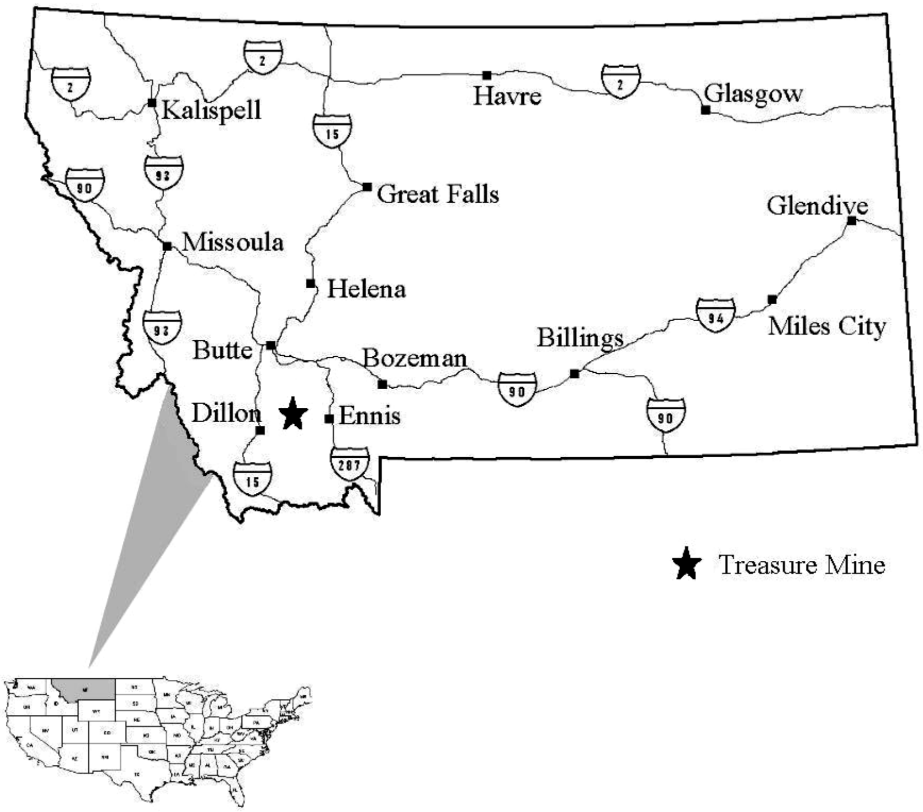


Figure 1. Location of Treasure Mine in southwest Montana.

The experiment was constructed on a regraded slope having a uniform slope gradient of 25 %. The five following biological, mechanical, and soil depth treatments were tested:

i) **Control**: Spoil backfill material graded to 25 % slope gradient.

ii) **Coversoil**: 30 cm thick coversoil application placed over spoil backfill material graded to a 25 % slope gradient.

iii) **Coversoil/Pitting**: 30 cm thick coversoil application placed over spoil backfill material graded to a 25 % slope gradient, with pitting. Pit dimensions were approximately 900 cm^3 and dug by hand. Pits were staggered in a checkerboard pattern with alternating rows of two and three pits. Distance between pits was 3.39 m.

iv) **Coversoil/Slash Barriers:** 30 cm thick coversoil application placed over spoil backfill material graded to a 25 % slope gradient, with four slash barriers (3.1 m wide by 0.8 m long) installed every 6.8 m along the slope. The slash barriers were constructed with lodgepole pine branches measuring 8 cm or less diameter cut fresh from nearby trees and anchored to the soil surface with wire and stakes. Fine branches and needles were allowed to remain on the branches. Branches were staked flush to the soil surface to prevent undercutting of the barriers by water.

v) **Coversoil/Vesicular Arbuscular Mycorrhizal Fungi Inoculm (AM Inoculum):** 30 cm coversoil application placed over spoil backfill material graded to 25 % slope gradient, with commercial mycorrhizal fungi inoculation. Pelletized AM inoculum provided by PHC Reclamation, Inc., was applied at 37.0 liters per hectare.

Each treatment was replicated three times in a completely random experimental design for a total of fifteen test plots. Each plot was 3.1 meters wide and 30.5 meters long and was bounded laterally by a silt fence to prevent sediment and runoff from flowing onto adjacent plots. A diversion ditch was constructed above the test plots to prevent upslope runoff from entering the plots. Sediment and runoff from eroding experimental plots was captured by a collection trough, recessed into the ground so that the upper lip of the trough was level with ground surface. Each trough was 3.1 m long by 1.2 m wide by 0.6 m deep. Trough capacity was designed to capture approximately 25 % of the runoff from a 24 hour – 100 year precipitation event, assuming no infiltration. The transitions between treatment plots and collection troughs were packed with bentonite clay to minimize undercutting between slope and trough.

Test plots were seeded with a mix of perennial grasses, shrubs and forbs in June, 2000. Seed was broadcast by hand and raked into the surface. An annual barley species, *Hordeum vulgare*, was included with the perennial seed mix to provide rapid cover. All plots were broadcast fertilized with 36-kg/ha nitrogen and 36-kg/ha phosphorus after the test plots had been constructed.

The AM inoculum was the pelletized form and applied at 37.0 liters per hectare. The commercial AM inoculum was provided by PHC Reclamation, Inc. Treatment plots were inoculated by broadcasting the inoculum onto 6 m long x 3 m wide subsections and then covering the pellets with 5 cm of coversoil. One hundred milliliters of AM inoculum was applied to each subsection, for a total of 500 mL of AM inoculum per treatment plot.

Soil physiochemical characteristics were determined by collecting composite samples of the spoil backfill test plots (Control treatment) and plots with coversoil (Coversoil, Coversoil/Pitting, Coversoil/Slash Barriers, Coversoil/AM Inoculum treatments). Composite soil samples were oven dried at 41° C and disaggregated using a mortar and pestle.

Coversoil texture was sandy loam. Chemical characteristics of the coversoil were all within ranges that are not limiting to plant growth (pH = 6.8, electrical conductivity (EC) = 0.9 mmhos/cm, sodium absorption ratio (SAR) = 0.1). Coversoil characteristics that could impair vegetation establishment and growth were the high coarse fragment percentage (49 % by weight and 38 % by volume) and low percentage (0.6) of organic matter.

The spoil backfill texture was sandy loam. Coarse fragment percentage was 64 % by weight and 51 % by volume, and organic matter was 0.1 %. Chemical characteristics of the spoil backfill (pH = 7.4, EC = 1.4 mmhos/cm, SAR = 0.8) were suitable for plant growth.

An on-site precipitation-recording gage located next to experimental plots monitored precipitation. A solar powered Campbell Scientific CR-10 datalogger recorded precipitation data on an hourly basis and in one-millimeter increments. Hourly measurements gave an indication of the intensity of various precipitation events.

A Class I evaporation pan was installed adjacent to the precipitation gage to measure evaporation at the site. A 200-liter capacity stilling well was connected to the evaporation pan by a hose and a constant water level in the evaporation pan was maintained using a float and valve check. The volume of water evaporated each hour was recorded using a Stevens recorder located in the stilling well and used to calculate evaporation (cm).

Runoff accumulated in collection troughs was measured every two weeks from late spring through early fall. Depth of water in the troughs was measured to the nearest millimeter. Precipitation falling into the trough and evaporation of water from the trough was accounted for using data collected from the precipitation gage and the evaporation pan.

Accumulated sediment in collection troughs was measured and collected every two weeks from late spring to early fall during 2000 and 2001. After water depth was measured, a submersible pump powered by a gasoline generator was used to remove the water from the troughs. Sediment was collected in 19-liter buckets using spades and shovels. Samples less than 22 kilograms were transported back to Montana State University, oven-dried at 41° C and weighed. Rill severity on experimental plots was classified during every monitoring cycle of the study period using the Erosion Condition Classification, Montana Revised Method [5].

During 2001, plant canopy cover, basal cover and aboveground plant biomass (biomass) were measured during the peak of the growing season. All three variables were analyzed by growth form (i.e., annual or perennial grasses, forbs). Transect locations were staked on all plots. These transects were along the diagonal, running from the upper left-hand corner to the lower right hand corner of each plot. Ten quadrats were sampled on each test plot to measure plant cover and biomass. Quadrats were placed every 3 m beginning at the 3 m point along the transect.

Canopy and basal cover were estimated using a 20 x 50 centimeter Daubenmire frame. Cover was estimated by growth form, i.e., perennial grass, annual grass, or forb. These cover values were averaged across quadrats to determine plant canopy and basal cover. Rock fragments, litter, and bare ground were also measured in terms of cover.

Biomass was measured using a 20 x 20 centimeter frame on the same quadrants used to measure cover. Vegetation within the frame was clipped two centimeters above the ground, sorted by growth form, and placed into paper bags. These samples were oven-dried at 49° C to a constant weight. Vegetation was weighed and biomass for each life form was calculated on a kg/ha basis.

A greenhouse study was conducted to determine whether propagules of mycorrhizal fungi were present in the coversoil and spoil backfill material prior to application of the commercial AM inoculum. Bulk composite samples were collected of the coversoil and spoil backfill material with a hand trowel every 3 meters along the slope. Hand trowels were thoroughly cleaned, rinsed and dried between plots. Each bulk composite sample consisted of 10 scoops from each treatment replication. Soils were brought to the Montana State University Plant Growth Center and planted with *Sorghum sudanese* (Sudan grass). Fifty seeds per pot were planted 2 cm deep and kept moist with a water mister until plants emerged. After germination, plants were culled to five per pot, and allowed to grow for 90 days, with a 14-hour photoperiod, a daytime temperature of 21^{o} C and a nighttime temperature of 18 ^{o}C. Roots were harvested and analyzed for presence of – and percent colonization of - AM fungi.

Percent of root length colonized by AM fungi was determined after clearing and staining root samples. Roots that had been washed free of soil were cut into 2 cm segments, cleared with 2.5 % KOH solution for 48 hours, soaked in HCl for 12 hours and stained with 0.05 % trypan blue stain in lactoglycerol. Two slides with twelve root segments per slide were made for every plant sample. Transects recording presence or absence of mycorrhizal structures were conducted across the roots. Ninety-six observations of root segments per plant were observed with 200-x magnification. The presence of AM hyphae, vesicles, arbuscules, or non-AM hyphae was recorded for each intersection.

Vegetation and the AM colonization levels were sampled during the second year of plant growth (August, 2001). Four plants of *Agropyron trachycaulum* and *Hordeum vulgare* were collected to a 30 cm depth from the Coversoil, Coversoil/AM Inoculum and Control treatment plots. Plants were transported in cold-storage to Montana State University laboratory facilities for analysis. Roots were examined to determine if mycorrhizal fungi were present.

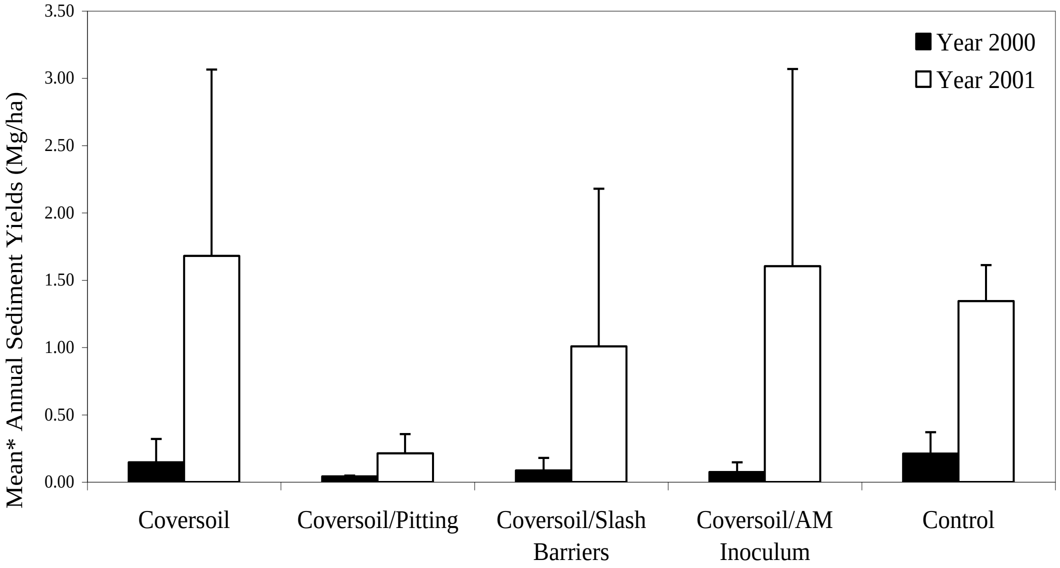
Analysis of variance techniques and mean separation tests were used to ascertain whether significant differences were present at the 95 % level of confidence ($P = 0.05$). Significant differences at $P \leq 0.05$ were separated using the Student-Newman-Keuls method of pairwise multiple comparison for equal size data sets. Least-squares regression was used to evaluate associations between independent and dependent variables. Multivariate associations were tested using multiple linear regression analysis. These analyses were made using SigmaStat version 2.0 software (Jandel 1995).

RUSLE version 1.06 is a DOS computer model [6]. Various input variables were required for each factor in the RUSLE model. Using mathematical equations, RUSLE estimated an average annual sediment yield. Input values were either from field data, from Renard et al. (1997) [7], or were provided by the United States Department of Agriculture Natural Resource Conservation Service State Agronomist [8].

Results and Discussion

Total annual sediment yield during 2000 was low (mean = 0.11 Mg/ha, n = 15), and increased during the second year (mean = 1.17 Mg/ha, n = 15). Figure 2 is a comparison of mean annual sediment yield by treatment for the study period. The low sediment yield for the first year was a result of infrequent, low-intensity precipitation. Total precipitation in 2000 was 24 % below normal annual rainfall at the Dillon WMCE, Montana recording gage. Sediment yield increased during the second year although total rainfall amounts in 2001 were 36 % below normal average annual rainfall at the Dillon WMCE, Montana recording gage. Greater sediment yield the second year was the result of two strong summer storm events during July and August, 2001. These two precipitation events generated more sediment yield than any other events during the two-year study period. Due to below normal precipitation, vegetative growth was negligible during the first year of the study and developed to an average of 15 % plant canopy cover in 2001. Although the soil surface was largely bare of vegetation during the first year, sediment yield was higher during the second year of study due to more erosive precipitation. The vegetative cover during the second year of the study was still not well developed.

Sediment yields were significantly lower on the Coversoil/Pitting treatment at the 10 % probability level of confidence during 2000. There were no significant differences between treatments during either year of study at the 5 % probability level. Sediment yields measured were highly variable except on pitted slopes. This variation could be attributed to rill formation that developed on some plots. Lower sediment yields measured on pitted slopes were attributed to minimization of rill formation on the soil surface. Rill formation provided a conduit for concentrated flow of water across the soil surface, increasing the velocity and erosivity of water moving downslope.



* Mean of three replications. Bars are one standard deviation

Figure 2. Comparison of mean annual sediment yields by treatment during 2000 and 2001.

In 2000, mean rill severity varied from stable to slight and there were no significant differences between any of the treatments. In the 2000 field season, sediment yield was dominated by sheet erosion and slight rilling and sediment yields were low. The Coversoil/Pitting treatment had significantly lower rill severity ratings than all other treatments during 2001.

Rill severity class was strongly related to sediment yield both years. In 2000, all test plots exhibited final rill severity classes of mostly stable or slight, which was showed a strong linear relationship with total annual sediment yield (r = 0.76). In 2001, total annual sediment yield showed a strong exponential relationship with mean rill severity class (r = 0.87). Test plots that were assigned with a rill severity class of moderate to critical showed an exponential increase in sediment yield at the point when rill severity class exceeded moderate levels. These data indicate that once rill formation occurred beyond the moderate rill severity class, sediment yields were accelerated.

Mean percent rock cover varied between 36 and 58 % during 2001 and the differences among treatments were not significant. Percent rock cover was not significantly related to sediment yield, runoff or rill severity class during 2001. Plant biomass was negatively related to rock cover in 2001 (r = -0.68).

Results from this study indicate that the decreased rock cover in the treatments with coversoil application (36 – 42 %) were associated with better plant growth and no significant decreases in sediment yields were provided by the increased rock cover in the control during this study.

Runoff was not significantly different between any of the treatments during 2000 and 2001. Runoff was strongly related to rill severity during 2000 but not during 2001. A possible explanation for the lack of relationship between rill severity and runoff in 2001 is that rilling increased on all test plots during July and August. During September, precipitation amounts similar to the previous storms generated runoff from the test plots but little to no sediment yield was measured.

Mean biomass, canopy cover and basal cover were significantly higher on plots with a coversoil application during 2001 when compared to the Control. However, there were no significant differences among treatments that received a coversoil application, indicating that the Coversoil/Pitting, Coversoil/Slash Barriers, and Coversoil/AM Inoculum treatments during the period of this study neither enhanced nor reduced plant growth when compared to the Coversoil treatment. Plant growth developed very slowly during the year 2000 due to low precipitation following seeding. Therefore, no plant measurements were made.

Plant growth was not related to sediment yield, runoff, or rill severity class in 2001. Although there was significantly more plant growth on the plots with coversoil compared to the control in 2001, the increased biomass and plant cover did not result in significantly less measured sediment yield or runoff. Low precipitation during 2001 contributed to slow plant development during the second season. Canopy cover (7 – 17 %) and basal cover (1 – 6%) were small and did not have a significant effect on sediment yield and runoff during 2001.

To determine whether propagules of mycorrhizal fungi were present in the coversoil and soil backfill material prior to application of commercial AM inoculum, *Sorghum sudanese* (Sudan grass) was planted in the coversoil and spoil backfill material sampled after experimental plot construction but prior to the application of the commercial AM inoculum. Mycorrhizal fungi propagules were present in the coversoil (39 %) and spoil backfill material (30 %, as evidenced by AM formation in *Sorghum* roots.

There were no differences in percent colonization of the roots by mycorrhizal fungi in *H. vulgare*. In *A. trachycaulum*, the AM inoculum treated plots showed significantly higher mycorrhizal colonization levels, as compared to plant roots from the coversoil and no coversoil treat plots. However, there were no significant differences between any of the above-ground plant growth characteristics on plots that received a coversoil application. Both plant species were colonized by AM fungi at a relatively high level, and there is probably no measurable ecological difference between 46 % and 53 % colonization rates. With such high colonization in both AM-treated and non-AM treated plots, we would expect to see no biomass differences between those treatments. AM inoculation in this study seems to have been unnecessary, since AM propagules were present in the coversoil and spoil prior to AM inoculation. This AM inoculation treatment was not found to enhance either AM inoculation levels or plant growth.

During the first year when sediment yields were low, RUSLE overpredicted mean sediment yields by 0.2 ± 0.2 Mg/ha. During the second year when larger amounts of sediment were moved, RUSLE on average underpredicted sediment yields by 1.0 ± 1.0 Mg/ha. RUSLE underpredicted sediment yields by 1.6 ± 0.9 Mg/ha on plots that had an average annual rill severity rating of greater than 1.5.

The rill formation factor constants calculated by Kapolka and Dollhopf (2001) were applied to the second year RUSLE analysis because rill formation was active [3]. The optimized RUSLE outputs are presented in Table 1. Appropriate F Factors were selected for individual plots based upon mean annual rill severity for 2001. The optimized RUSLE estimated sediment affect a soil's potential for rilling. Yields on average overpredicted sediment yields only slightly by 0.03 ± 0.41 Mg/ha. The optimized sediment yields improved accuracy of the RUSLE predictions to within 97 % of the measured sediment yields. These results provide evidence that the rill formation factor established by Kapolka and Dollhopf to reflect the larger sediment yields during active slope rilling at the Treasure Mine retains accuracy under different rainfall conditions. The rill formation factors may not apply to soils that have different physiochemical characteristics.

Table 1. Optimized RUSLE sediment yields (Mg/ha) using rill formation factors during 2001.

	RUSLE Factors							
Treatment	**R**	**K**	**F**	**K1**	**LS**	**C**	**P**	**Optimized RUSLE Sediment Yields**
Coversoil	13	0.15	1.0	0.15	4.32	0.06	1.0	0.23
Coversoil	13	0.15	8.4	1.26	4.32	0.06	1.0	1.91
Coversoil	13	0.15	16.6	2.49	4.32	0.06	1.0	3.78
Coversoil/Pitting	13	0.15	1.0	0.15	0.78	0.13	1.0	0.09
Coversoil/Pitting	13	0.15	1.0	0.15	0.78	0.13	1.0	0.09
Coversoil/Pitting	13	0.15	1.0	0.15	0.78	0.13	1.0	0.09
Coversoil/Slash Barriers	13	0.15	1.0	0.15	1.52	0.09	1.0	0.12
Coversoil/Slash Barriers	13	0.15	16.6	2.49	1.52	0.09	1.0	1.99
Coversoil/Slash Barriers	13	0.15	1.0	0.15	1.52	0.09	1.0	0.12
Coversoil/AM Inoculum	13	0.15	16.6	2.55	4.32	0.06	1.0	3.87
Coversoil/AM Inoculum	13	0.15	1.0	0.15	4.32	0.06	1.0	0.23
Coversoil/AM Inoculum	13	0.15	8.4	1.26	4.32	0.06	1.0	1.91
Control	13	0.12	8.4	1.01	4.32	0.05	1.0	1.19
Control	13	0.12	8.4	1.01	4.32	0.05	1.0	1.19
Control	13	0.12	8.4	1.01	4.32	0.05	1.0	1.19

The influence of the mechanical treatments (Coversoil/Pitting and Coversoil/Slash Barrier) in decreasing sediment yields was evaluated by calculating the ratio of sediment yield from the mechanical treatment and sediment yield from the Coversoil treatment to obtain a sediment-yield delivery ratio (Table 2). The sediment-yield delivery ratio was 0.14 for the Coversoil/Pitting treatment and 0.60 for the Coversoil/Slash Barriers. These mechanical treatments are intended as short-term, temporary erosion control measures to provide adequate slope stability until vegetation is established. It is expected that the pits will gradually fill in with eroded soil and the slash barriers will degrade over time, and the resultant sediment-delivery ratios will correspondingly increase.

Table 2. Measured sediment-delivery ratio values for Coversoil/Pitting and Coversoil/Slash Barrier treatments.

Treatment	Sediment Delivery Ratio
Coversoil/Pitting	0.14
Coversoil/Slash Barriers	0.60

Conclusion

Results indicate a trend towards pitting of the soil surface as a potentially effective erosion control practice to prevent rill formation and reduce erosion rates. The Coversoil/Pitting treatment consistently had decreased sediment yield on all plots and within treatment variation was minimal. Sediment yields on all other treatments were highly variable. This variation could be attributed to rill formation that developed on some plots. Lower sediment yields measured on pitted slopes were attributed to the increased surface roughness on the soil surface prohibiting the downslope linear trajectory of water flow and minimizing rill formation. Newly constructed coversoil and spoil backfill are highly erosive materials and susceptible to rilling especially when precipitation is intense. Pitting of the soil surface also increases slope storage of water. Therefore, erosion control efforts that increase the surface roughness such as pitting or gouging are ideal for mineland reclamation on steep slopes until vegetation is established. A good vegetative cover may take two or more years to develop. The short duration of the study (two years), limited vegetation development (≤ 17 % canopy cover), and low replication (n = 3) all limit the ability to detect treatment differences. Therefore, these results suggest that pitting of the soil surface is potentially an effective erosion control practice at the level of precipitation received during the study, preventing rill formation and reducing sediment yields on steep slopes until vegetation can provides adequate slope stability.

Mycorrhizal propagules were present in both coversoil and waste rock material collected before application of AM inoculum. *Sorghum sudanese* had 30 % and 39 % AM root colonization levels, respectively. After two growing seasons, there were no significant differences in percent AM root colonization of *Hordeum vulgare* harvested from no coversoil (34 %), coversoil (34 %), and coversoil/AM inoculum (35 %) treatments. *Agropyron trachycaulum* harvested from AM inoculum treated plots showed significantly higher AM colonization levels (53 %) compared to the non-inoculated coversoil (46 %) and no coversoil treatments (44 %). AM inoculation treatment was not found to enhance aboveground plant growth. Plant growth was significantly lower on the no coversoil treatment, but there were no differences between those remaining treatments that received 30 cm of coversoil.

Although RUSLE version 1.06 overpredicted mean sediment yields by 0.2 ± 0.2 Mg/ha during 2000 and underpredicted by 1.0 ± 1.0 Mg/ha in 2001, estimates of sediment yields were close to actual sediment yields. Rill formation factor constants were applied to the 2001 data when rilling was moderate or greater, which improved RUSLE's ability to predict sediment yield to within 97 % of measured sediment yield. The sediment-delivery ratio was 0.14 for the Coversoil/Pitting treatment and 0.60 for the Coversoil/Slash Barriers.

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