Effect of mechanical and biological enhancements on erosion at high elevation disturbed lands
by Susan Rhea Winking

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Rehabilitation
Montana State University

Abstract:
The objective of this study was to evaluate the effect of erosion control measures on sediment yields on reclaimed steep slopes at the Treasure Mine, MT and compare measured sediment yields to values predicted by Revised Universal Soil Loss Equation (RUSLE) Version 1.06.

Plots were constructed on a regraded waste rock area having a uniform 25 % slope. 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. Plots received identical application of seed and fertilizer.

Total annual sediment yields for test plots were low during 2000 (mean 0.11 Mg/ha) and increased in 2001 (mean 1.17 Mg/ha). There were no differences in mean sediment yield by treatment in both years. There was a trend on pitted slopes for lower sediment yield in 2000 and significantly lower rill severity rating in 2001. 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.

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.

Prior to implementation of field treatments, Sorghum Sudanese grown in the greenhouse in coversoil and waste rock material collected before application of AM inoculum had 39 % and 30 % 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 did not enhance aboveground plant growth.

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.

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

by

Susan Rhea Winking

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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1. 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 (Toy & Foster, 1998). 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 (Toy & Foster, 1998).

Erosion hazards increase when vegetative cover is lost, soil permeability is low, and the ground increasingly slopes, especially if soils are shallow (Brooks et al., 1997). 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 (Toy & Foster, 1998). This research focuses on mechanical practices that reduce the energy of flowing water and biological enhancements to stimulate vegetative growth to reduce soil erosion on high elevation steep slopes.

Investigative Objectives

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.

2. LITERATURE REVIEW

Erosion Control Regulations

Soil erosion control continues to be a significant challenge to agriculture as well as industry resulting in poor water quality due to sediment (Renard & Ferreria, 1993), geomorphological downstream impacts such as channel change (Knighton, 1998), loss of soil resources (Toy & Foster, 1998) and transport of adsorbed chemicals (Renard & Ferreria, 1993). Because of this, there has been increasing demand by regulatory authorities on industry to provide erosion analyses as a part of their land management plans.

Since the 1970's, the United States and the State of Montana have passed legislation that places more stringent environmental controls on mining and mineral extraction operations. For example, erosion control measures have been specifically targeted under the U.S. Surface Mining Control and Reclamation Act and the Clean Water Act (U.S. Congress, 1977; U.S. Congress, 1972). Montana environmental laws place strict erosion control measures on the mining industry as well. Table 1 provides examples of legislation concerning soil erosion on coal and metal mines in Montana.

Revised Universal Soil Loss Equation (RUSLE)

The main processes influencing soil erosion by water are raindrop impact and subsequent transport of soil by flowing water. Accelerated erosion is considered to be occurring when soil erosion rates exceed 0.2-0.5 Mg/ha (0.1-0.2 tons/ac) annually, which

Table 1. Examples of Montana legislation mandating erosion control.

Montana Mining Law	Citation	Intent
Strip & Underground Mine Siting Act	82-4-202 MCA*	Requires approved reclamation plan that includes erosion control measures before permit will be issued.
Strip & Underground Mine Siting Act	82-4-231 MCA	Mining operation must take all measures to prevent damages to the people and property by soil erosion.
Strip & Underground Mine Siting Act	82-4-231 (10) (c) MCA	The mine operation must impound, drain, or treat all runoff or underground mine waters so as to reduce soil erosion.
Strip & Underground Mine Siting Act	82-4-231 (11) MCA	All stockpiled materials resulting from land disturbances must be within permit boundaries and cannot erode off-site.
Strip & Underground Mine Siting Act	82-4-233 MCA	The vegetative cover must be capable of preventing soil erosion to the extent achieved prior to the operation.
Metal Mine Reclamation Act	82-4-336 MCA	Reclamation plan must provide that reclamation activities, particularly those relating to control of erosion, to the extent feasible, must be conducted simultaneously with the operation.
Metal Mine Reclamation Act	82-4-434 (2) (g&l) MCA	The department may not approve a reclamation plan or a plan of operations unless the plans provide that: ▪ all access, haul, and other support roads will be located, constructed, and maintained in such a manner as to control and minimize channeling and other erosion; ▪ seeding and planting will be done in a manner to achieve a permanent vegetative cover that is suitable for the postmine land use and that retards erosion.

*MCA = Montana Code Annotated

is the rate at which soil lost to wind and water is replenished by weathering of parent material on undisturbed lands, i.e., geological erosion (Brady & Weil, 1996). Erosion is a two-fold process in which the soil particles are detached and then forces cause rolling, dragging and splashing of the particles and induce transport by water (Brady & Weil, 1996). Detachment is initiated by such processes as freezing and thawing, overland water flow, and raindrop splash applying shear stress upon soil particles. Raindrop splash and flowing water transport the loosened soil particles (Brady & Weil, 1996; Knighton, 1998).

The Revised Universal Soil Loss Equation (RUSLE) equation includes five factors; the erosivity potential of rainfall and runoff, soil erodibility, hillslope length and slope, plant cover and management, and erosion control support practices (Toy & Foster, 1998). This factorial approach to estimating annual average soil loss is the result of a set of empirically-derived mathematical equations that have evolved from almost a century of intense erosion research in the United States.

Up until the 1950's, soil and earth scientists were estimating soil loss based on equations that were formulated in very specific geologic and climatic areas and were therefore limited in their range of applicability (Renard et al., 1997). The United States Department of Agriculture, Agricultural Research Service (USDA, ARS) formed the National Runoff and Soil-Loss Data Center in 1954. The purpose of the Center was to collect and assimilate soil loss data. Data used to develop the USLE and RUSLE consisted of erosion-plot research collected from natural rainfall events and simulated rainfall in which water was applied to erosion plots (Toy & Foster, 1998). The erosion plots were 72.6 foot long by either 6.0 or 12.0 foot wide (0.01 or 0.02 acres). The mathematical relationships between each factor and soil loss were determined by regression analysis. This analysis led to the formulation of the Universal Soil Loss Equation (USLE):

$$A = R \circ K \circ LS \circ C \circ P$$

Where:
- A = Average annual soil loss in tons/acre/year
- R = Rainfall/runoff erosivity
- K = Soil erodibility
- LS = Hillslope length and steepness
- C = Cover-management
- P = Support practices

(Toy & Foster, 1998; Renard et al., 1997)

This equation should have universal validity because none of its factors utilized a reference point that has direct geographic orientation (Toy & Foster, 1998).

The Revised Universal Soil Loss Equation uses the same formula, but with updated and improved calculations for the contributing factors (Renard et al., 1997). Although there are many other models such as WEPP, ANSWERS, AGNPS, EPIC that predict erosion, RUSLE is the most widely used prediction tool to date because of ease of use, availability of parameter data, acceptable accuracy, and readily acceptable assistance from USDA Natural Resources and Conservation Service (NRCS) personnel (Renard & Ferreira, 1993; Toy & Foster, 1998; Renard et al., 1997; Yoder & Lown, 1995). It is also the only water erosion prediction model adopted by all states in the United States for predicting sheet and rill erosion (USDA NRCS, 2000).

R – Rainfall/Runoff Erosivity

The R factor in RUSLE represents the rainfall/runoff erosivity and reflects the climatic contribution of precipitation to soil loss. The rainfall factor reflects the relationship between total storm kinetic energy (E) times the maximum 30-minute intensity (I_{30}) (Toy & Foster, 1998). Volume of rainfall and runoff specify the storm energy (E). Prolonged peak rates of detachment and runoff are accounted for in the (I_{30}) component. Total energy and peak intensity are combined in each particular storm to produce the statistical interaction product term EI, which is an abbreviation for energy times intensity. Technically, the term indicates how particle detachment is combined with transport capacity (Renard et al., 1997). R is equal to the average annual sum of EI_{30} for storm events during a rainfall record of at least 22 years (Toy & Foster, 1998). When erosion is dominated by spring thawing and snowmelt, an equivalent R value (Req) that accounts for these processes is used (Toy & Foster, 1998; Renard et al., 1997).

K- Soil Erodibility

The soil erodibility factor is a numerical value representing the average, long-term susceptibility of soil and soil profile to a large number of erosive and hydrologic processes (Renard et al., 1997). The K factor lumps the soil and soil profile reaction to these processes into an integrated average annual value (Renard et al., 1997). The RUSLE software can vary K values seasonally to account for temporal variability in the processes (Renard & Ferreira, 1993). These processes consist of soil detachment and transport by raindrop impact and surface flow, localized deposition due to topography and tillage induced roughness, and rainwater infiltration into the soil profile (Renard et al., 1997). If the soil is undisturbed, K values can be obtained from published NRCS Soil Survey data. Otherwise, RUSLE software will calculate an estimated K using a soil-erodibility nomograph. This nomograph combines a series of equations that estimate K based on texture (percent sand, silt, and clay), percent organic matter, soil structure, soil permeability class and percent coarse fragments. Although RUSLE K factor was specifically developed for soil properties equivalent to tilled agricultural soils, it is appropriate on reclaimed soils because the handling and management of soil material on disturbed sites often results in equivalent soil properties (Renard et al., 1997).

LS – Hillslope Length and Gradient

The LS factor in RUSLE is a combined parameter integrating length and gradient of a hill. Soil loss increases as both slope or length increases because runoff accumulates and accelerates downhill (Renard et al., 1997). The erosive force and velocity of water increases with increasing slope (Toy & Foster, 1998). The ratio of rill (concentrated) to interrill (diffuse) erosion on the hillslope is used to determine the effect of hillslope length on soil loss, and is high for silty and recently disturbed soils and low for clayey and sandy soils. It is a function of soil texture and general land use (Toy & Foster, 1998).

The hillslope length factor L has a value of 1 for a "unit plot" which is defined as 72.6 feet in length with a gradient of 9 percent (Renard et al., 1997). The L value is less than 1 for hillslope lengths less than 72.6 feet and greater than 1 for lengths greater than 72.6 feet. If soil loss results from interrill erosion, which is assumed to be uniform along a hillslope, the L value will be 1 for all lengths. If rill erosion is the main process, the L factor will increase linearly with length because rill erosion increases in the downslope direction as runoff accumulates (Toy & Foster, 1998).

The hillslope gradient factor, S, reflects the effect of hillslope-profile gradient on soil loss. For a unit plot, with a 9% gradient, the S value is equal to 1. The S values vary from above to below 1, depending on whether the gradient is greater than or less than that of the unit plot. Soil loss increases more rapidly as gradient increases than as length increases. Also, rill erosion is affected more by hillslope gradient than is interrill erosion (Toy & Foster, 1998).

Within RUSLE, the hillslope length (L) and gradient (S) terms are combined into a single topographic factor (LS) representing the ratio of soil loss from a given hillslope length and gradient to soil loss from the unit plot (72.6 feet in length, 9% gradient). Thus, LS values are not absolute values but are based upon a value of 1 for unit plot conditions. Because land use has a large impact on rill erosion, it is as important to select the proper RUSLE land use category as it is in determining hillslope length and gradient. The RUSLE software will calculate the LS factor based upon assumptions that the rill to interrill ratio is low, moderate or high for a given land use selected.

C - Cover-Management

The cover-management factor (C) represents the effects of vegetation and management on soil loss. As with other RUSLE factors, the C value is a ratio comparing the existing surface conditions at a site to the standard conditions of the unit plot.

The C factor represents the effect of plants, soil covers, roots, incorporated residue, and soil-disturbing activities on soil loss. RUSLE offers a time-variant or time-invariant option. The time-variant option is to model situations where changes in soil and vegetation are anticipated to greatly affect erosion. The time-invariant scenario is used to estimate erosion on a stable landscape.

Four subfactors are normally used to estimate the C value: prior land use, canopy cover, surface cover and surface roughness. In the Northwest Wheat and Range Region of the United States, an additional subfactor representing antecedent moisture is added.

The C-factor is one of the most important factors in the RUSLE equation because it represents surface soil conditions that can be manipulated by land managers to prevent erosion, and the numerical C value calculated based on the above sub-factors can range from almost 0 to a little more than one, thus having a large weighted value on the total estimated annual soil loss (Toy et al., 1999).

P – Support Practices

The support practice factor (P) represents erosion control practices such as contouring and terracing that reduce erosion (Renard et al., 1997). The P sub-factors that are multiplied together to estimate an overall P value are based upon whether a time-variant or time-invariant option was selected when computing the C value. If a time-invariant scenario is being modeled, the sub-factors used to calculate P are contouring and other mechanical disturbances. If the time-variant option is chosen, P is calculated based on contouring, permanent barrier strips, concave hillslope shapes, terracing and/or sediment basins and subsurface drainage. The RUSLE model is able to assess the effectiveness of the various support practices by weighing their effectiveness against information listed in other factors. For example, contours are less effective where rainfall/runoff erosivity is high (Toy & Foster, 1998).

The sediment-delivery ratio is associated with the terracing subfactor (Renard et al., 1997 and Toy & Foster, 1998). When sediment production in the inter-terrace interval exceeds the transport capacity of the flow in the terrace channel, deposition occurs and the sediment-delivery ratio is less than 1. When the transport capacity equals or exceeds the soil loss, the sediment-delivery ratio equals 1, indicating that all of the sediment is removed from the hillslope by the channel flow. The soil loss estimated by RUSLE can be multiplied by the sediment-delivery ratio to estimate the amount of sediment leaving the hillslope. The same principles are used to estimate the sediment-delivery ratio for concave hillslope profiles. If sediment ponds or basins are used to retain sediment on-site, then the soil loss from hillslopes can be multiplied by the sediment-delivery ratio to estimate the sediment discharged into a sediment pond (Toy et al., 1999).

Improved Accuracy Representing Effect of Slope Steepness

RUSLE experts consider the slope steepness factor, S, to be moderately accurate for slopes over 20%. In a study done by Nearing (1997), the RUSLE functions used for the effect of slope steepness on soil loss by water were linear functions of the sine of the slope angle. Two linear functions are used in RUSLE: one for slopes <9% and another for >9%. By using the original data used to calculate the current linear functions used by RUSLE along with what was considered to be the best data for steeper slopes, a single, continuous logistic function was derived that he contends is equivalent to the current functions in RUSLE for slopes <25% and is better for slopes >25% (Nearing, 1997).

RUSLE and Geomorphology

Toy and Osterkamp (1995) investigated the applicability of RUSLE to geomorphological studies because of anticipated use of the model for these purposes despite the fact that analysis at geomorphic scales are outside of the model's intended scope. They indicate that soil loss estimates may be extended into the past as long as the environmental conditions remain virtually the same as those used in the computations. Soil loss estimates are likely to be of satisfactory accuracy at spatial scales ranging from landscape (hillslope) profiles to small drainage basins where channel processes of aggradation and degradation are insignificant (Toy & Osterkamp, 1995).

Database Sensitivity of RUSLE

Renard and Ferreira (1993) performed a sensitivity analysis of the three databases used in the RUSLE modeling software. They compared the percent change in a parameter to the resulting percent change in predicted soil loss. In their examination of the CITY database, which represents geographic location and associated climate, the RUSLE model was very sensitive to changes in the city codes. The CITY database contains the rainfall/runoff (R) values for locations throughout the United States. Temperature values were found to be significantly more important in estimating annual soil loss values than precipitation. This was attributed to the effect of temperature on residue decomposition. The authors stress that sensitivity will vary geographically and the RUSLE may react in unpredictable ways. Sensitivity analysis should be performed based on local modeling situations, and can be a very helpful tool when allocating resources for field data collection (Renard & Ferreira, 1993).

Use of RUSLE on High Elevation, Steep Slopes

Kapolka and Dollhopf (2001) calculated a rill formation factor using nonlinear variable estimation (Kapolka & Dollhopf 2001). 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.

Opportunities for research include calibrating the RUSLE model for use on reclaimed lands, testing the model against applications for which it was not designed (such as mine spoil piles), investigating process-based relationships between the factors as opposed to the empirically-based relationships used now and creating methods that standardize the measurement of variables. Additional areas that would assist disturbed land reclamation efforts are further testing of erosion control measures for input into the P factor.

RUSLE is the most widely used model for estimating average annual soil loss because of its accuracy and flexibility (Yoder & Lown, 1995). In Montana, many mining companies and environmental consulting firms are using RUSLE version 1.06 software to estimate potential erosion resulting from mining activities. RUSLE and other erosion models are being used in a variety of settings by state and federal regulatory authorities as well. The estimated annual soil loss estimated by the RUSLE model may be a part of the information used for approving final reclamation plans, pre-and post-mining permits, and reclamation bond release. Use of models requires expertise and a full understanding of inputs, outputs, and a sound background when science-based estimates are required using variable data is needed or applying RUSLE to a new setting. It is important for both industry and the regulatory authorities to understand the intricacies and limitations of the erosion models.

Commercial Mycorrhizal Fungi Inoculations in Mineland Reclamation

Mycorrhizae are a plant-fungal symbiosis found in possibly 95 % of the world's plants (Smith & Read, 1999). The mycorrhizae fungus receives carbon from the plant and in return enhances plant uptake of nutrients, particularly phosphorus and trace minerals (Smith & Read, 1999).

Factors related to mining practices that decrease or eliminate a viable population of mycorrhizal fungi are i) removal of vegetation; ii) topsoil storage; and, iii) disturbance of the soil (Jasper et al., 1987; Miller & Jastrow, 1992). Topsoil stockpiling can reduce the density of mycorrhizal fungi in the soil (Rives et al., 1980; Gould & Liberta, 1981; Liberta, 1981, Abdul-Kareem & McRae, 1984), depending on length of time soil is stockpiled and soil moisture content. This reduction in mycorrhizal fungi can be detrimental to not only the grass, forb, and shrub seedling establishment (Visser et al.,