Evaluation of amendments for a topsoil substitute at the Stillwater Mine
by Heidi Jill Kaiser

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

Abstract:
Topsoil is an invaluable resource for use in reclamation of disturbed lands. It is often in short supply, particularly when dealing with disturbances related to underground mining. The paucity of topsoil available at the Stillwater Mine, a platinum group metals mine in south central Montana, prompted a study evaluating an alternative for native topsoil materials at the site.

The subject of this study is the crushed rock or cuttings produced by the Tunnel Boring Machine which was utilized during the underground mining process at the Stillwater Mine. This crushed rock is considered waste and is disposed of through ongoing construction of the tailings impoundment, portal sites, and access roads. The cuttings contain no phytotoxic materials and are barren of essential plant available nutrients. They are comprised of about 50 percent loamy sand (<2 mm particle diameter), 15 percent small rock fragments (2 mm to 5 cm) and 35 percent coarse materials (>5 cm) Revegetation trials on the cuttings were initiated in the fall of 1988 with the construction of test plots. Five mulch treatments were applied to the cuttings in combination with organic and inorganic fertilizer applications. The plots were seeded with drought tolerant species adapted to the climate of the mine site. Plant growth was evaluated by measuring percent canopy cover and biomass production during the first and sixth growing seasons.

Results of the revegetation trials indicated that there were no major significant differences in the response of plant cover or production among the different mulch treatments in 1989 or 1994. There were, however, significant differences among the plant responses to the fertilizer subtreatments in both years. Plant production was enhanced by the addition of phosphorus to the Biosol in 1989 and by both the mineral fertilizer and Biosol + P in 1994. We may infer that the addition of extra phosphorus as a mineral fertilizer or as an amendment to Biosol is necessary to maximize perennial grass and forb production in the materials used as a coversoil substitute at the Stillwater Mine.

EVALUATION OF AMENDMENTS FOR A TOPSOIL SUBSTITUTE AT THE STILLWATER MINE

by

Heidi Jill Kaiser

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Land Rehabilitation

MONTANA STATE UNIVERSITY

Bozeman, Montana

November 1995

APPROVAL

of a thesis submitted by

Heidi Jill Kaiser

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.

8 Dec 1995 — Frank F Munshower

Date — Chairperson, Graduate Committee

Approved for the Major Department

12/11/95 — [signature]

Date — Head, Major Department

Approved for the College of Graduate Studies

12/23/95 — [signature]

Date — Graduate Dean

STATEMENT OF PERMISSION TO USE

In presenting this thesis (paper) in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Signature Heidi J. Kaiser

Date November 30, 1995

ACKNOWLEDGMENTS

I would like to thank Stillwater Mining Company for providing the material resources for initiating this field study and for financial assistance for the completion of this thesis. I wish to express my vast appreciation to Dr. Frank F. Munshower for his guidance and assistance with this project and for all his help and patience throughout the duration of my extended graduate career. I would also like to thank the other members of my graduate committee, Mr. Dennis Neuman and Dr. Douglas Dollhopf, for the help they provided with this project.

The support, patience, and good humor of my husband, family, friends, and co-workers was critical to the completion of this Master's degree.

TABLE OF CONTENTS

TABLE OF CONTENTS. Continued

LIST OF TABLES

LIST OF TABLES. Continued

LIST OF FIGURES

ABSTRACT

Topsoil is an invaluable resource for use in reclamation of disturbed lands. It is often in short supply, particularly when dealing with disturbances related to underground mining. The paucity of topsoil available at the Stillwater Mine, a platinum group metals mine in south central Montana, prompted a study evaluating an alternative for native topsoil materials at the site.

The subject of this study is the crushed rock or cuttings produced by the Tunnel Boring Machine which was utilized during the underground mining process at the Stillwater Mine. This crushed rock is considered waste and is disposed of through ongoing construction of the tailings impoundment, portal sites, and access roads. The cuttings contain no phytotoxic materials and are barren of essential plant available nutrients. They are comprised of about 50 percent loamy sand (<2 mm particle diameter), 15 percent small rock fragments (2 mm to 5 cm) and 35 percent coarse materials (>5 cm)

Revegetation trials on the cuttings were initiated in the fall of 1988 with the construction of test plots. Five mulch treatments were applied to the cuttings in combination with organic and inorganic fertilizer applications. The plots were seeded with drought tolerant species adapted to the climate of the mine site. Plant growth was evaluated by measuring percent canopy cover and biomass production during the first and sixth growing seasons.

Results of the revegetation trials indicated that there were no major significant differences in the response of plant cover or production among the different mulch treatments in 1989 or 1994. There were, however, significant differences among the plant responses to the fertilizer subtreatments in both years. Plant production was enhanced by the addition of phosphorus to the Biosol in 1989 and by both the mineral fertilizer and Biosol + P in 1994. We may infer that the addition of extra phosphorus as a mineral fertilizer or as an amendment to Biosol is necessary to maximize perennial grass and forb production in the materials used as a coversoil substitute at the Stillwater Mine.

INTRODUCTION

Topsoil is an invaluable resource for use in reclamation of disturbed lands. It is often in short supply, particularly at disturbances related to underground mining. The purpose of this study was to enhance reclamation efforts at the Stillwater Mine by amending waste material to make it suitable for use as a coversoil during current and post mining reclamation activities.

During 1988 the Stillwater Mine employed a tunnel boring machine (TBM) to drive access adits to the ore zone. The grinding action of the rotating TBM cutter head created a greater portion of fine material in the cuttings than was generated during the conventional "drill and blast" method of advancing these adits. The rock encountered during the advance of the access adits is primarily an unweathered quartz monzanite. This crushed rock is essentially devoid of plant available nutrients, organic matter, and phytotoxic elements but it does have a greater water holding capacity than conventional waste rock because of the greater amount of fines in the TBM cuttings.

Reclamation of surface disturbances at the Stillwater Mine is concurrent with mining activities where it is possible. Revegetation is carried out to minimize erosion, decrease the visual impact of mine related disturbances, and provide forage for wildlife. For example, portal pads at adit entrances are constructed of light colored waste rock which creates a barren slope below the portal. Mining permits require that these slopes have minimal visual impact. In addition, access roads to portals are often constructed by cut and fill operations.

These roads must also blend visually with the surroundings. Topsoil or coversoil (if it exists) is removed before new construction and redistributed in the appropriate areas or stockpiled for final reclamation. Unfortunately, topsoil frequently is lacking or is of poor quality where these disturbances are located.

In an attempt to alleviate the problem of the topsoil deficit, substitutes for coversoil were examined at the Stillwater Mine. One alternative was the use of crushed rock produced by the TBM. These geologic materials do not contain plant available nutrients or organic matter. The elements necessary for vegetative establishment must be added to the mining waste to correct the deficiencies of these essential soil components. The objective of this study was to develop an alternative for topsoil by determining optimum fertilizer and mulch treatment(s) needed to sustain vegetative growth on TBM cuttings.

LITERATURE REVIEW

Most hard rock mining disturbances are found in or near alpine environments. They have not received the intensive review and research associated with coal mining activities. An important factor when dealing with high-elevation disturbances is the poor quality and insufficient quantity of topsoil generally found in this environment (Brown et al. 1978). These factors and effects of disturbing existing topsoil have led to research emphasizing organic enrichment of waste rock and other available soil materials as substitutes for surface soil coverings. The research carried out in these environments has contributed to a basic understanding of reclamation problems regarding plant species selection, soil fertility, and soil texture in these settings.

For example, reclamation of mining disturbances on the Beartooth Plateau, the location of several precious metals mines, has been studied by many scientists since the 1970's (Brown et al. 1976, 1978; Chambers et al. 1984; Guillaume 1984). Brown, Chambers and others found that organic matter incorporated into the surface of alpine soils together with fertilizer greatly enhances plant establishment. Guillaume's study supports these ideas and presents the finding that native species are better suited to alpine sites due to their adaptation to low growing temperatures and short growing seasons.

Other research at hardrock mine reclamation projects includes studies conducted at the Berkeley Pit in Butte, Montana, where Parady (1981) and Lawson (1984) used alluvial materials as coversoil to assist the revegetation of acidic waste dumps. The alluvial materials they used created soil crusts which were alleviated with the addition of organic matter. At the Zortman and Landusky Mines in north-central Montana, Spry (1986) concluded that low water availability was the main factor limiting revegetation trials on waste rock dumps and tailings. These trials did not involve the use of any topsoil cover on waste rock. The use of composted municiple waste was the subject of a revegetation study at the Basin Creek Mine carried out by Vodehnal (1993). This site straddles the continental divide near Helena, Montana. Vodehnal found that the composted waste enhanced seedling germination and plant establishment.

Topsoil vs Coversoil

Topsoil is defined as the surface soil which generally has a greater organic matter content than the deeper subsurface soil. It provides a good rooting medium, reduces runoff, improves infiltration, encourages faster reestablishment of nutrient cycles and increases species diversity of the vegetation cover (Schuman and Power 1981). Topsoil can be viewed as an amendment which accelerates the reclamation process. Microorganisms present in topsoil facilitate organic matter decomposition and are very important in renovating soil structure and cycling macronutrients. One of the greatest assets of topsoil is its texture (particle size distribution) which is important to soil/plant water relationships. Soil texture affects several critical factors of revegetation of disturbed sites (Sabey et al. 1987). These factors include moisture, temperature, aeration, root penetration, chemical activity and erosion.

Adequate revegetation requires a suitable growth medium, preferably and ideally topsoil, but this growth medium may be a material which does not meet all of the criteria associated with the definition of topsoil. Coversoil is a more appropriate term for those materials which may be salvaged from any soil horizon other than the A Horizon. Coversoil must be nontoxic and have a texture that will hold water for plant growth. If coversoil or other growth media satisfy these requirements, the nutrient and organic constituents can be provided by amendment with organic matter and fertilizer (Brown 1984a). Daniels and Amos (1984) reviewed the use of topsoil substitutes for reclamation in the southern Appalachian coal fields. They found that once rocky spoils (topsoil substitutes) are revegetated, the morphological, physical, chemical and mineralogical properties of the cover soil change quickly as the material weathers into mine soil.

Soil Texture

A growth medium available at the Stillwater Mine is TBM cuttings. This material is approximately 50 percent loamy sand with a percentage of small rock fragments created by the action of the TBM. While rock fragments (>2 mm) are not always considered desirable in topsoil materials they do have positive effects on the quality of soils in terms of reclamation potential. Some of these positive attributes include reduced susceptibility to erosion and compaction (Munn et al. 1987). Rock fragments also increase the macro porosity of soils which enhances water infiltration into the soils (Edwards et al. 1984). Water will penetrate to a greater depth in rocky soils compared with nonrocky soils of similar texture (Birkland 1984).

The fine or soil fraction (<2 mm) of the TBM cuttings is comprised of sand (0.05 to 2 mm), silt (0.002 to 0.05 mm) and clay (<0.002 mm) particles. The relative proportion of these particles in soil directly affects water infiltration, soil aeration, cation exchange capacity and erodibility (Munshower 1994). Coarse or sandy soils allow water to pass through the soil without retaining enough water for plant use. Fine soil particles such as clay, reduce permeability and retard water movement from the surface down into the soil. Clay soils retain water once the water enters the soil profile. Sometimes the water is held to tightly to be absorbed by plants. Silt loams or silts hold large quantities of water for plant growth even though much of this water is unavailable to plants (Lyle 1987). A soil with an intermediate texture, that is, a soil with enough sand to allow for aeration and looseness to permit plant root growth and development and enough clay for adequate nutrient and water-holding capacity would be ideal for reclamation.

Fertility

The two most limiting plant growth nutrients on mine soils in the western United States are nitrogen and phosphorous (Bauer et al. 1978). Fertilizer applications were also found to be absolutely essential to the successful and rapid establishment of plant cover on alpine disturbances (Brown 1984b). Nitrogen can be the most difficult nutrient to control because it remains in the soil for only short periods of time. Soil nitrogen is lost through plant uptake, rainwater leaching, use by microorganisms, and volatilization. A single application of fertilizer nitrogen for vegetation establishment may be inadequate to sustain the vegetation because nitrogen fertilizers may be depleted within a few weeks after application. Lyle (1987) recommends application of half of the nitrogen fertilizer before seeding and the other half 30 or 45 days following seeding. The need to re-apply nitrogen fertilizer during a single growing season may be eliminated by applying a slow release type of fertilizer. The long term nitrogen needs of vegetation (many years) may be met by planting nitrogen fixing plant species. Legumes add significant levels of nitrogen to geologic materials through nitrogen fixation. It is estimated that sweet clover can fix from 100 to 200 kg N/ha per year (Stevenson 1982). Often state reclamation laws require the use of native species and will not allow introduced legume species. However, at the Stillwater Mine site, sweet clover has proven to be a valuable forage species which holds up well under intense grazing pressure by the bighorn sheep of the area.

Plants need relatively large amounts of phosphorous but the amount available is often low in soils. Seedling development is very restricted when soils are deficient in this element. Despite adequate applications of nitrogen, grasses usually exhibit very limited growth on phosphorus deficient soils (Follet et al. 1981). Legumes which are helpful in reestablishing pathways for rapid nitrogen cycling (Reeder 1990) are also sensitive to phosphorous availability. They require larger amounts of this nutrient than most other plant species.

Potassium, another important macro nutrient, is necessary for normal lignin and cellulose development in plants. Cellulose and lignin contribute strength and stiffness to plant cell walls (Follet et al. 1981). Potassium also encourages root development. This is an important factor for plants on sandy soils with low water holding capacity. Plants with an abundance of roots are able to utilize soil moisture efficiently. This improves their drought resistance. Fortunately, young western soils are rarely lacking adequate quantities of this element.

Organic Matter and Soil Biota

Decomposition and mineralization of organic matter provides a steady supply of nutrients especially nitrogen and phosphorus for plants (Smith et al. 1987). The organic fraction of soil holds over 99 percent of the soil nitrogen supply. When the organic matter content of the surface soil is adequate, nitrogen fertilization of disturbed soils is not necessary (Munshower 1994, DePuit and Coenenberg 1979, Rennick et al. 1984). Organic matter in soils also enhances the water holding capacity by increasing water absorption and retention (Brandt and Hendrickson 1991). This is especially important in sandy or skeletal soils. Addition of organic matter to clayey textured soils often reduces soil crusting (Parady 1981) and increases infiltration and percolation rates.

Organic matter consists of the decaying remains of plants and animals as well as living microorganisms. The residues may be fresh material on the ground surface, older partially decomposed particles in the soil, or materials which have been broken down to smaller organic molecules. Humus, the primary constituent of organic matter, is produced as plant residues decompose. Soil organisms are an important component of organic matter and include bacteria, fungi, insects, earthworms and small animals (Smith et al. 1987). The functions of these organisms include fragmentation of plant matter, soil mixing, and releasing plant nutrients such as nitrogen, phosphorous and sulfur.

A group of microorganisms key to revegetation success are the mycorrhizal fungi. The structures (mycorrhizae) formed by these fungi increase the surface area of plant roots. This increases the area available to the plant for the absorption of water and nutrients (Raven et al. 1981). This enhanced nutrient absorption potential created by the mycorrhizae can be a critical factor for plants on reclaimed soils of low-fertility. Many plants seem to grow normally when they are well supplied with essential elements, even if mycorrhizae are lacking; however, if the essential elements are limited, plants grow poorly or not at all when they lack mycorrhizae (Brady 1974). The role of mycorrhyzae in the direct transfer of phosphorous from the soil to the roots of plants has been documented (Raven et al. 1981).

Many forest trees are dependent on mycorrhizal associations for normal growth under natural conditions. Reid and Grossnickle (1978) found that tree seedlings transplanted to soils barren of mycorrhizal fungi generally did not survive unless the seedlings or soil was inoculated with the fungi. Seedlings can be inoculated in the nursery and transplanted to the reclamation site (Cordell et al. 1987). In a study by Sopper and Seaker (1987) municiple sewage applied to mine spoils in Pennsylvania facilitated the rejuvenation of microbial populations including mycorrhizae in the spoils.

Soil microbial parameters have been used to study the rate of recovery of reclaimed land. Enzyme activities, ATP levels, and soil respiration have been used by Stroo and Jencks (1982), Schafer et al. (1979), and Visser et al. (1983) to describe the development of microbial activities in mine soils. Allen (1984) studied the effects of disturbance on mycorrhizae and concluded that any practice which sustained the plant mycorrhizae relationship enhanced vegetation establishment

Coversoil, material which is likely to be lacking in organic matter, including microorganisms, should be amended to encourage mycorrhizae populations as well as populations of other microoorganisms. For any reestablishment of vegetation it is essential that microbial activity is restored to ensure carbon and nutrient turnover. Organic matter and fertilizer will greatly enhance the reestablishment of microbial populations (Fresquez et al. 1986).

Mulches

Successful revegetation of coarse soils materials requires the application of mulch at the time of seeding in order to hold the soils as well as the seed in place. Mulches are most often organic materials applied to the surface of a disturbance after seeding. Mulches, when incorporated, are organic amendments and create pronounced impacts to soil structure, infiltration, cation exchange capacity and nutrient cycles (Munshower 1994). At the Stillwater site where high winds are common year round, mulches hold the seed in place and retain moisture for seedling/plant uptake. Kay (1978) noted that mulches serve to enhance infiltration of water into the soil and moderate surface temperatures. They also provide physical protection from the kinetic energy of raindrops and create minidams which help to hold water where it falls thereby encouraging infiltration and minimizing runoff (Duell 1989). In a study by Kay (1974) the use of straw mulch increased plant establishment in decomposed granite. Adverse effects of straw mulch include the possible immobilization of nitrogen during decomposition (Berg 1980), interception of light and the creation of a possible physical barrier to seedling development.

Biosol - An Organic Fertilizer

Biosol is a slow release organic fertilizer product consisting of dried granular fungal mycelial material. It is more than 70% organic matter and contains major and minor nutrients. While it has been shown to stimulate plant establishment (Naschberger and L. Köck 1983), it is more costly than mineral fertilizers.

Most of the research conducted with this material has been carried out in alpine environments. The terrain in these areas is usually very steep and soils are highly erodible when disturbed. One study comparing materials for erosion prevention at high altitudes (Badawy and Schönthaler 1983) found that Biosol increased the effectiveness of protection against soil erosion. This was due to the fact that within one or two days after application a dense network of hyphae developed in the top layer of the soil (1-2 cm). These hyphae retard soil erosion by water. A study by Glatzel and Fuchs (1986) compared Biosol to mineral fertilizer when applied to surface soils planted with spruce seedlings. The Biosol treated seedlings responded with better growth, a more complex root system, and needles had a deeper green color than plants receiving only mineral fertilizer. High altitude abandoned mine sites in Idaho's Payette National Forest were hyrdroseeded and fertilized with Biosol in 1992. Rohlman (1993) reported high seed germination and excellent plant survival on these sites which were topsoil deficient.

MATERIALS AND METHODS

Site Description

The Stillwater Mine is an underground platinum and palladium mine located in the Stillwater River valley 8 km south of Nye, Montana, and approximately 130 km south west of Billings, Montana (Figure 1). The mine is situated in the Beartooth Mountains. The elevation at the mine ranges from 1,525 m above mean sea level (msl) at the Stillwater river to 1,920 m above msl at the uppermost adit. The mine site including portal areas, mill, and tailings pond, is situated in an area formerly occupied by chromium milling and mining activities. Bighorn sheep have historically used this area as a winter range because high winds reduce snow cover to a minimum on these exposed slopes.

Conventional mining methods are used to drive adits and extract ore at the Stillwater Mine but three of the major access adits were driven with a tunnel boring machine (TBM) in 1988 and 1989. The waste rock produced by the TBM contains a greater amount of fine ground rock than conventionally produced waste rock. The test plots described in this text were constructed of this TBM waste rock. They are located east of the Stillwater River on level terrain which had not been disturbed by mining activities (Figure 1).

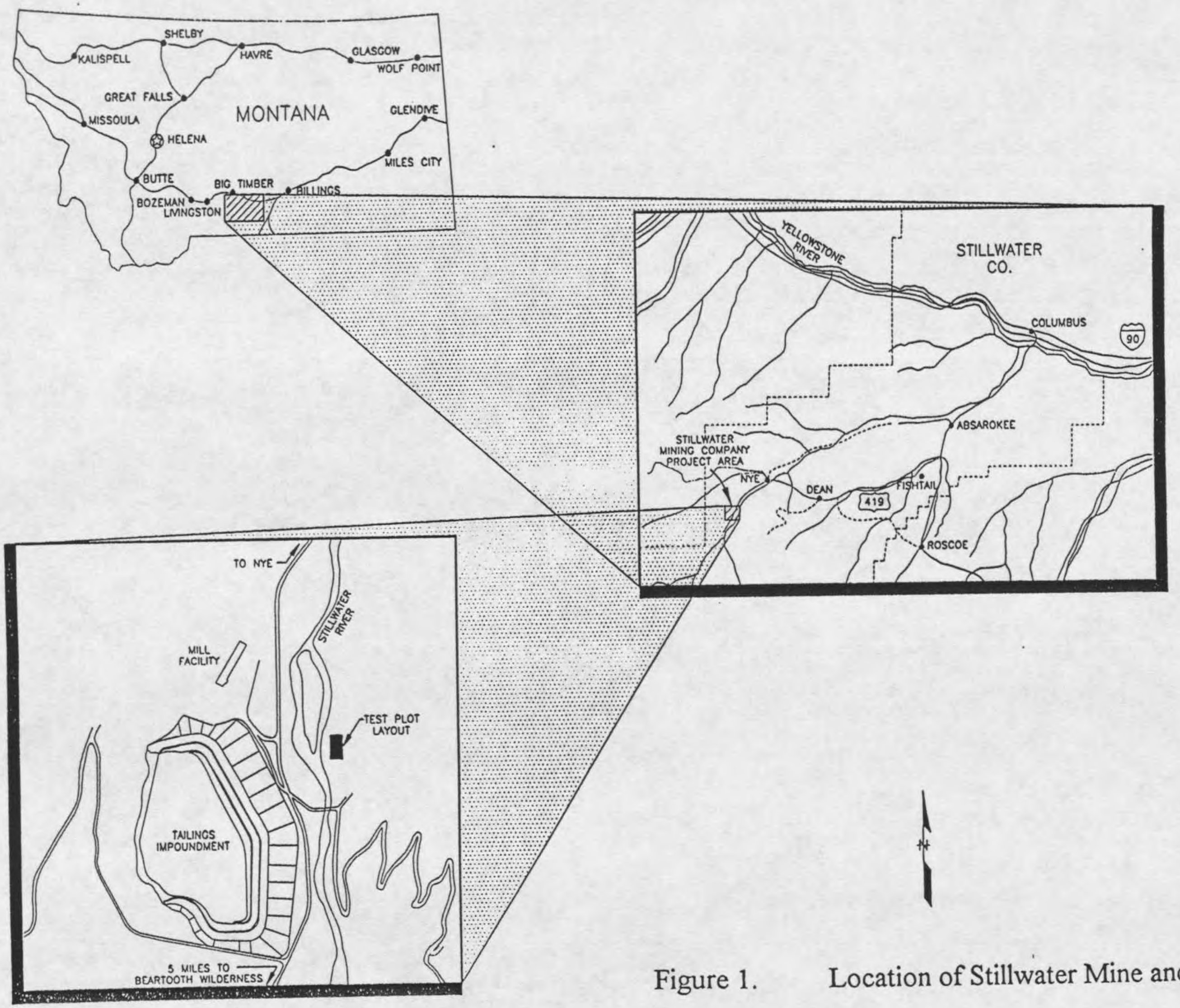

Figure 1. Location of Stillwater Mine and Test Plots

Field Plot Design

In December 1988, several yards of TBM cuttings were hauled, dumped and graded to approximately 60 cm thick in a near level, undisturbed area immediately east of the Stillwater River (Figure 1). The study plots were placed on these graded materials. The field plot design was a split plot with complete randomized blocks (Snedecor and Cochran 1978) in three replications, with five mulch treatments and three fertilizer sub-treatments. Plots were staked, 183 cm on each side with a 183 cm alley between replications. One seed mix comprised of drought tolerant species adapted to the site was seeded on all plots during December 1988.

The plot configuration is shown on Figure 2 and mulch treatments and fertilizer subtreatments are identified in Table 1.

Table 1. Mulch treatments and fertilizer sub-treatments applied to TBM cuttings.

Main Plot ID	Mulch	Application Rate
WF-1	Wood Fiber	2,800 kg/ha + 110 kg/ha tackifier
WF-2	Wood fiber	5,600 kg/ha
Grass	Pelleted Grass Matter	2240 kg/ha
Straw	Wheat Straw	2240 kg/ha
None	No Mulch	
Sub-Plot ID	**Fertilizer**	**Application Rate**
1	Mineral (27-18-0)	220 kg/ha
2	Biosol	1120 kg/ha
3	Biosol plus P_2O_5	1120 kg Biosol/ha + 45 kg P_2O_5/ha

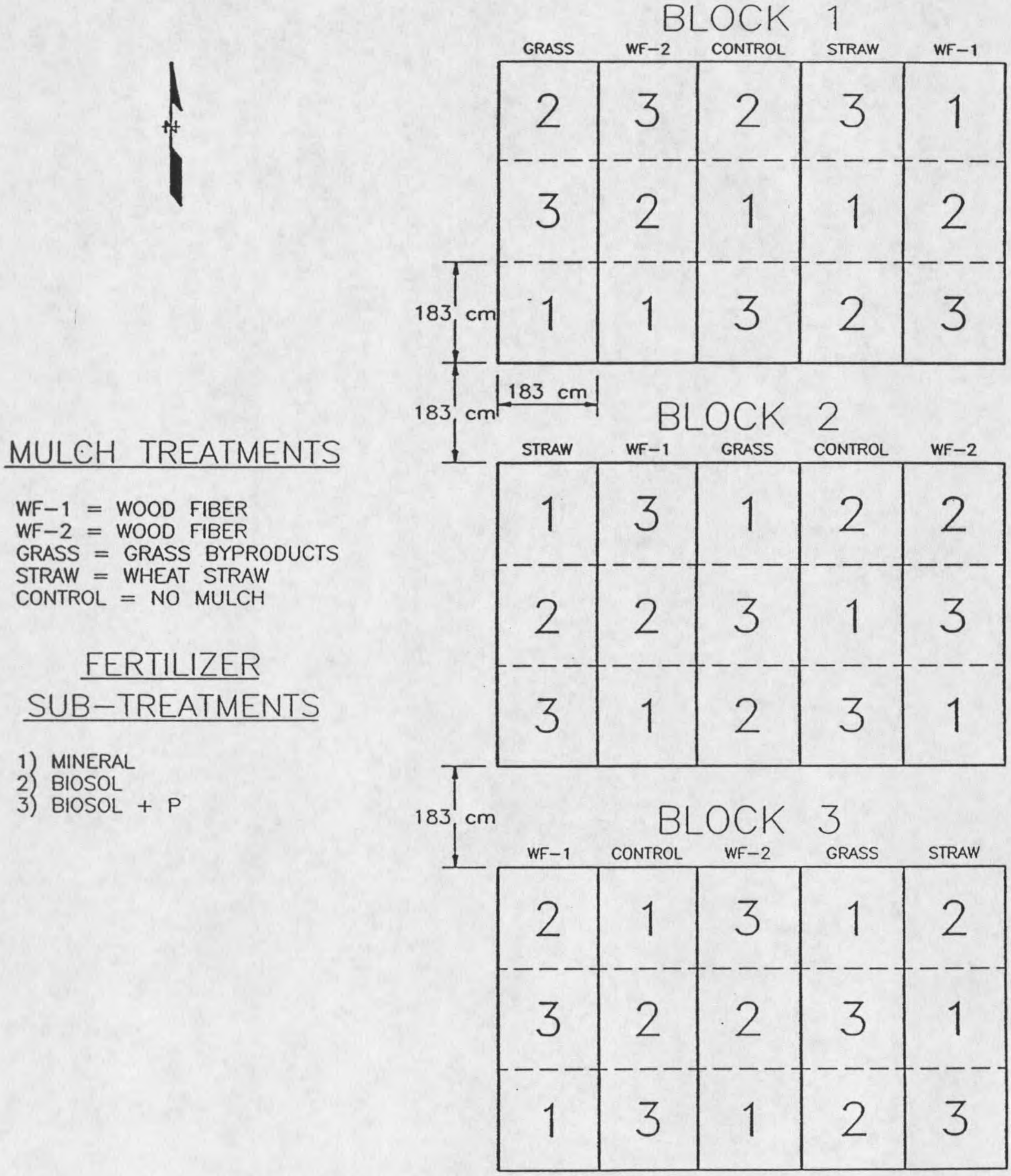

Figure 2. Field plot design implemented on the TBM cuttings

Mulch Treatments

Three different types of organic mulches were used on the test plots. Two of these mulches, the wood fiber and the pelleted grass were applied as hydromulch. The wood fiber, Silva-Fiber, has been used successfully at the Stillwater site with only minor problems caused by high winds. It was applied at two different rates (2,800 kg/ha and 5,600 kg/ha) with the addition of a tackifier to provide added protection against wind and water erosion. The second mulch consisted of sun-cured grass seed, stems and hulls which is pulverized, steam heat-treated, concentrated and pelletized. This pelletized mulch was applied at one rate (2,240 kg/ha). A tackifier was also used with this mulch.

Straw was applied as a fourth treatment. It was applied by hand at approximately 2240 kg/ha and crimped into the surface of the cuttings by tracking with a small dozer. This technique had previously been used on level and gently sloping areas of the mine site. The straw used on the test plots was wheat straw secured from a local source. A seeded and fertilized control plot with no mulch application was the fifth treatment.

Fertilizer Sub-treatments

Fertilizer application rates were based on laboratory analysis of the TBM cuttings. The plant available macronutrients in the TBM cuttings were compared to plant nutrient needs for emergence and establishment in order to arrive at estimated appropriate application rates of the selected soil fertilizers. All fertilizer treatments were broadcast by hand and incorporated into the surface with a fixed tooth harrow.

A mineral (inorganic) fertilizer with an N-P_2O_5-K_2O content of 27-18-0 was incorporated at a rate of 220 kg/ha. Ammonium nitrate and diammonium phosphate were blended to produce this mix.

Biosol, a plant growth stimulator developed in Austria, consists of 70 % organic matter (Rocky Mountain Bio-Products). The source of organic material in Biosol is dried granular fungal mycelial material, a by-product from the manufacture of penicillin. The composition of Biosol is 90 percent dried biomass (dry mycelium) and 10 percent potassium-magnesia. The nutrient content is 6 % nitrogen, 1 % P_2O_5 and 3% K_2O.

Two subtreatments of Biosol were incorporated at 1120 kg/ha. One was incorporated with additional phosphorous (diammonium phosphate) at 45 kg P_2O_5/ha (Table 1). The other treatment was applied without any additional phosphorous.

Seed Mix

Native plant species and those suitable for establishing in the sandy loam texture of the TBM cuttings were included in the species mix (Table 3) seeded on the test plots. Other factors taken into account when choosing the species were forage value and ease of establishment.

Indian ricegrass (*Oryzopsis hymenoides),* a cool season perennial bunch grass, is well established in the Stillwater valley. It is an excellent forage plant and is one of the first perennial grasses to become reestablished on sandy sites after disturbances (Taylor and Lacey 1994). Indian ricegrass is especially abundant in areas of sandy soils where wind has deposited chromium tailings from the chromium ore processing of the 1940's. These soils

Table 2. Plant species seeded on TBM cuttings

Scientific name*	Common name	Pure live seed/ m^2
Grasses		
Agropyron dasystachyum	Thickspike wheatgrass "Critana"	107
Agropyron spicatum	Bluebunch wheatgrass "Secar"	75
Agropyron trachycaulum	Slender wheatgrass "Revenue"	65
Orzyopsis hymenoides	Indian ricegrass	75
Calamovilfa longifolia	Prairie sandreed	129
Festuca ovina	Sheep fescue	86
Forbs		
Linum lewisii	Blue flax	75
Meliolitus alba	White sweet clover	86

* Scientific names taken from Hitchcock and Cronquist 1973.

are also vegetated by prairie sandreed (*Calamovilfa longifolia*) and western wheatgrass (*Agropyron smithii*). Thickspike wheatgrass (*Agropyron dasystachyum)* was seeded instead of Western wheatgrass because of the coarse texture of the wastes. Bluebunch wheatgrass *(Agropyron spicata*) and sheep fescue (*Festuca ovina*) were added to the seed mix because they are the dominant grass species on undisturbed native grasslands of the study area. Slender wheatgrass (*Agropyron trachycaulum*) was seeded as a nurse crop. It develops early but dies out of the community as the other perennial grasses mature.

White sweet clover (*Meliolitus alba*) was included in the mix as a source of nitrogen and for forage value. This clover has been used in revegetation seed mixes at the Stillwater

Mine where it has performed well as a soil stabilizer and as a reliable source of forage for the bighorn sheep native to the area. Blue flax *(Linum lewisii)* was added to the seed mix to increase plant diversity and enhance the appearance of the plant community.

Seeding took place during December so that the germinating seeds could take advantage of moisture that accumulated during the winter storms.

Characterization of TBM cuttings

A grab sample of the TBM cuttings was collected from a waste pile. Due to the nature of the TBM cuttings, i.e. composed of freshly ground and unweathered quartz monzanite, plant available nutrients were assumed to be low in these materials. In order to define the plant available nutrients, a sample of the fine earth portion of the TBM cuttings was chemically and physically characterized. The sample was screened to determine the amount of coarse fragments. Analytical parameters, laboratory procedures, and references for these analyses are summarized in Table 3.

Field Plot Implementation and Vegetation Monitoring

During December 1988, the plots were ripped, seeded, fertilized and mulched. After the cuttings were graded to near level, a dozer ripped the surface to a depth of 7 to 15 cm. The plots and subplots were staked, fertilizer sub-treatments broadcast by hand, and seed applied with a hydroseeder. This was accomplished by adding seed for the entire plot layout to 2,800 liters of water and applying this mixture to the site. The fertilizer and seed were

Table 3. Methods of chemical and physical analysis of TBM cuttings.

Parameter	Procedure	Reference
pH	saturated paste	US Salinity Staff (1954), Meth 21a
Ammonium Nitrogen as N	KCl extraction	Thomas (1982), Meth.84-2
Nitrate as N	potassium choride ext.	Thomas (1982), Meth. 84-2
Phosphorous as P	Olsen Method ($NaHCO_3$)	Thomas (1982), Meth. 73-4
Available K	ammonium acetate extraction	Thomas (1982), Meth. 71-3
Cu, Cr, Fe, Mn, Zn	DTPA extraction	Follet and Lindsay (1970)
Ca, Mg, Na	ammonium acetate ext.	Thomas (1982)
Sodium adsorption ratio (SAR)	$Na/[(Ca+Mg)/2]^{1/2}$	US Salinity Staff (1954)
Conductivity	water saturated paste extraction	Sandoval and Power (1977)
Percent moisture at saturation	saturated paste	Bower and Wilcox (1965)
Particle size distribution	hydrometer, sieve, screen	Day (1965)

incorporated into the cuttings (2 to 3 cm deep) by pulling a fixed tooth harrow over the plots. Mulch treatments on the plots were applied on top of the seed and fertilizer sub-treatments.

Plant canopy cover and production were measured in mid July 1989, during the first growing season. Percent cover was estimated in two 20 x 50 cm frames (Daubenmire 1959) randomly placed within each plot. Production was determined by clipping the above ground biomass within these same frames. Vegetation was grouped by plant life form for cover estimation and biomass determination. The plant materials were oven dried at 60° C for 72 hours prior to weighing.

During July, 1994, five years after the first episode of monitoring, vegetation measurements were made on the plots for a second time. Cover and production data were collected in the same manner as in 1989.

The cover and production data from 1989 and 194 were analyzed using a two-way repeated analysis of variance (ANOVA) on two factors. Multiple mean comparisons were based on Least Significant Differences (LSD) at a significance level of 0.10. Statistical analyses were performed using the MSUSTAT statistical package (Lund 1993). ANOVA and LSD tables are included in Appendix B.