Assessment of land reclamation characteristics and maintenance techniques to promote long-term sustainability of reclaimed areas in Butte, Montana
by Cole Michael Mayn

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

Abstract:
Historical, large-scale mining activities in Butte, Montana have created the largest EPA superfund site in the northwest. Mine wastes with high trace element concentrations located in residential areas pose threats to human health and the environment. Reclamation of mine waste began in the early 1980's. Since initial reclamation, a decline in vegetation has been observed on various reclaimed sites, which could result in future land degradation problems.

This research was conducted in two phases. Phase I involved the assessment of fourteen previously reclaimed areas in Butte to determine if relationships existed between coversoil properties and the current success levels in the vegetative cover of reclaimed sites. The Phase I assessment included the investigation of factors that may be contributing to satisfactory or poor vegetative conditions on Butte reclaimed areas. Coversoil properties, weather statistics, and reclaimed site characteristics were correlated with plant canopy cover values. The Phase I assessment determined that coversoil depth was the significant variable influencing reclamation success in Butte. Reclamation sites with at least 56 centimeters (22 inches) of coversoil were predicted to contain successful total plant canopy cover values (>60%). Coarse fragments, silt, clay, as well as the nitrogen concentration of the coversoil were also found to be important for promoting successful plant cover.

The Phase II study involved the establishment of field test plots on two reclaimed areas in Butte, Montana. The effectiveness of inter-seeding, nitrogen fertilizer application, compost incorporation, and various combinations were evaluated over a two-year period. A herbicide weed treatment was incorporated on half of each test plot during the second year of research. Vegetative measurements were collected at the end of each growing season to determine if the treatments significantly improved plant biomass and canopy cover when compared with control values. Seeded species failed to establish on all inter-seeding treatments. Nitrogen fertilizer in combination with weed treatment produced significant improvements in existing plant canopy cover and biomass when compared to control plot values. Surface compost incorporation improved resistance to weed invasion;. however, the compost did not create significant improvements in existing plant canopy cover or biomass values. Additional time may be required before significant improvements in plant growth are observed from this treatment.

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Cole Michael Mayn

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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ABSTRACT

Historical, large-scale mining activities in Butte, Montana have created the largest EPA superfund site in the northwest. Mine wastes with high trace element concentrations located in residential areas pose threats to human health and the environment. Reclamation of mine waste began in the early 1980's. Since initial reclamation, a decline in vegetation has been observed on various reclaimed sites, which could result in future land degradation problems.

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CHAPTER 1

INTRODUCTION

Over one hundred years of underground and open-pit copper mining has substantially altered the landscape in Butte, Montana, leaving behind numerous mine waste piles and seriously degrading land quality within the Butte city limits. The contamination poses threats to human health and the environment. As a result, in 1983 the Environmental Protection Agency (EPA) placed Butte on the National Priority List for cleanup under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA). The reclamation of mine waste piles and highly impacted areas began in the early 1980's (*ARCO, 1998*). Since reclamation began, many sites with adequate initial vegetative canopy cover values later declined (*Troutman, 1997*). Various treatments, aimed at improving vegetative cover and reducing soil erosion, have been attempted on numerous reclaimed sites. However, many reclaimed areas still require maintenance or complete repair of the coversoil cap to restore adequate vegetative cover.

Thesis Objectives

Research objectives for this thesis are as follows:

1. Evaluate soil properties across a range of Butte reclaimed sites to assess coversoil suitability for plant growth with greater than 60% total plant canopy cover according to Daubenmire measurements.
2. Test the effectiveness of several vegetation enhancement techniques to improve plant canopy cover and vegetative sustainability.
3. Make recommendations of best management practices to enhance plant canopy cover and sustainability on existing Butte reclaimed areas.

This research was conducted in two phases to satisfy the above objectives. Phase I involved the assessment of vegetative cover, coversoil properties, and additional site variables on fourteen previously reclaimed sites. The Phase I assessment was designed to determine key variables that are associated with current vegetative success on Butte reclamation. Phase II involves the establishment of field test plots to assess potential reclamation maintenance techniques. This field research evaluated the effectiveness of inter-seeding, nitrogen fertilization, use of compost, and various combinations of these treatments to enhance plant canopy cover and biomass values on Butte reclaimed areas. Recommendations for best management practices on Butte reclaimed sites are based on the Phase I assessment and Phase II treatment results.

Butte Mining History

Placer mining in the Butte area began along Silver Bow Creek in 1864 (*Shovers et al., 1991*). These rather modest beginnings soon developed into large-scale underground mining operations on the Butte Hill, which were consolidated by the Anaconda Mining Company in the 1880's. Millions of tons of copper ore were mined in underground shafts and sent to smelters located around Butte and Anaconda. By 1956, the majority of large-scale underground mining ceased and open pit mining at the Berkeley Pit began (Figure 1). The Berkeley Pit developed into a large open pit mine that was designed to remove and ship high volumes of copper ore to Anaconda smelters (*Shovers, et al., 1991*). In the course of a century of mining, from 1870 to 1970, nearly $22 billion in copper, gold, silver, and other precious metals were removed from the Butte Hill establishing its reputation as "The Richest Hill on Earth" (*Butte Historical Society, 1985*).

Atlantic Richfield Company (ARCO) purchased the Anaconda Mining Company's mining claims in 1977. However, ARCO ceased all Berkeley Pit mining activities in 1982 due to falling copper prices, rising production costs, foreign competition, and environmental problems (*Anaconda-Butte Heritage Corridor, 1993*). Before the Berkeley Pit shutdown, a new open-pit mine, the Continental Pit, located east of the Berkeley Pit was opened and the mining legacy continued. The Continental Pit was acquired from ARCO by Washington Construction in 1986 and has been mined since then under the corporate name of Montana Resources (*Shovers et al., 1991*).

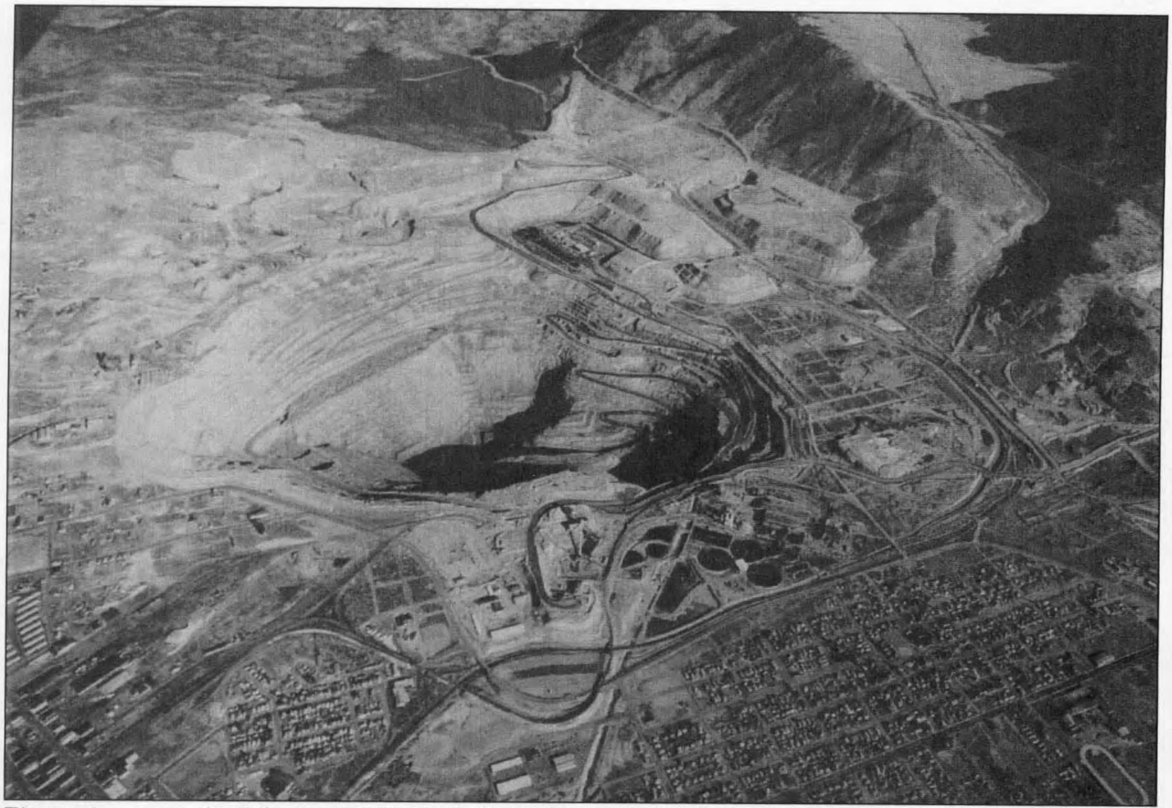


Figure 1. Aerial view of the Berkeley Pit and major disturbances created by the large mine. The photo was taken in the early 1980's shortly before mine closure.

Environmental Impacts

Over one hundred and thirty years of mining in Butte has substantially impacted the environmental integrity of the Butte Hill and surrounding areas. Associated with copper extraction and processing were enormous volumes of waste rock, tailings, and smelter emissions. Low pH mine wastes with high sulfide and iron pyrite concentrations were stockpiled at numerous locations across uptown Butte (*BPSOU PRP Group, 2000*). Some of these mine waste piles can be seen in the historical photo in Figure 2.

The mine wastes contain high concentrations of toxic trace elements, including many heavy metal and arsenic compounds that are hazardous to human health and the environment. Trace element contamination has impacted soils on both mining disturbed and undisturbed native areas in the Clark Fork River basin. Tailings ponds and mine waste piles cover thousands of hectares in the Butte and Anaconda area. Uncontrolled smelter emissions over an extended period of time polluted even larger expanses of land through aerial deposition (*U.S. EPA, 1998*).

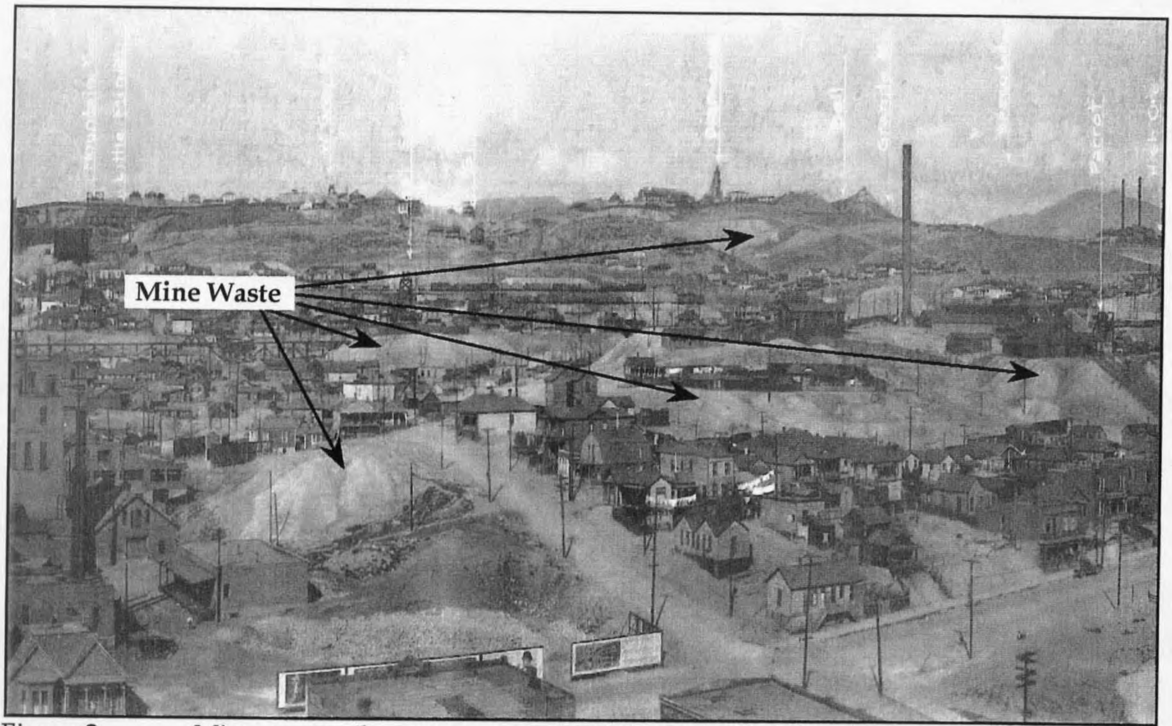


Figure 2. Mine waste piles were accumulated throughout Butte residential areas due to limited available space, cost, and convenience. The photo displays the conditions of uptown Butte, Montana in 1925.

The EPA adopted the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) in 1980. Numerous risk assessments were performed in the Butte and Anaconda area in the early 1980's. Based upon the assessment results, numerous mining impacted areas were placed on the National Priority List (NPL) in 1983 for cleanup under superfund (*Shovers, 1998*). The EPA designated ARCO, the current property owners, as the overall potentially responsible party, requiring the company to pay for the remediation of mining and smelting damages throughout the area (*BPSOU PRP Group, 2000*). Throughout the 1980's and early 1990's, a number of CERCLA superfund sites were identified in the Clark Fork River basin. The EPA administered several Time-Critical Removal Actions (TCRAs) to enforce the timely cleanup and/or removal of hazardous mine waste on the Butte Hill in response to immediate threats to human health and the environment. A large portion of Butte reclamation performed to date has been completed under EPA ordered TCRAs. Prior to EPA ordered TCRAs in the early 1980's, ARCO performed voluntary remedial actions involving mine waste removal, recontouring, coversoil placement, and revegetation on various sites. The Abandoned Mined Lands Bureau and Butte-Silver Bow County also performed mine waste removal and attempted revegetation on numerous sites in the early 1980's (*MSE, 1992*).

Hard Rock Mining Reclamation Challenges

A number of factors make reclamation challenging in hard rock mining situations. In many cases, hard rock mining occurs in areas with mountainous terrain. Reclamation may need to be performed on steep slopes due to limited available space and high costs associated with grading and moving overburden. The establishment of productive vegetation on steep slopes can be difficult due to limitations of reclamation equipment. Increased runoff and excessive coversoil erosion may hinder plant establishment and survival on steep slopes. Coversoil sources are often scarce and/or contain poor physical and chemical properties due to the geology in many hard rock mining areas. Good quality topsoil is a luxury and in most cases geologic substrata are used as coversoil (*Bradshaw & Chadwick, 1980*). These geologic materials are often biologically sterile, lacking adequate concentrations of soil organic matter and soil microorganisms. The sterile soil conditions often limit plant available nutrient levels and as a result hinder plant growth (*Veverka, 1998*). Elevated trace element concentrations are commonly associated with ore bodies at hard rock mines. As a result of phytotoxic element concentrations, mine wastes accumulated by the mining processes are often unsuitable for plant growth. The coversoil "cap" placed over the mine waste often provides the only suitable rooting medium for vegetation. Adequate coversoil depths may not be used due to limited coversoil availability and the high costs associated with coversoil handling. Limited plant cover on shallow coversoils may in turn result in increased coversoil erosion. Revegetation activities conducted in a semi-arid climate can be further challenged by weather conditions. The amounts and timing of precipitation in dry climates can have a considerable impact on vegetation establishment and productivity. Even when all reclamation and revegetation practices are performed correctly, plant establishment can still be hindered and oftentimes fail due to hot and dry conditions present during the growing season.

Topography

Steep slope reclamation, while generally not recommended, is performed in many hard rock mining situations due to the high costs of moving large volumes of overburden and limited available space at most mine sites (*Leavitt et al., 2000*). Reclaimed slopes steeper than a ratio of 3:1 or 33% are not generally recommended due equipment limitations and the probability of increased erosion. Plant performance can be hindered on steep slopes due to a lack of water infiltration into the soil. Runoff, or the potential for runoff, increases with increasing slope length and slope steepness. Frequent erosion can create rills and gullies degrading the soil resource and eventually killing vegetation that was intended to provide coversoil stability. Vegetative failure often leads to mass coversoil wastage and re-exposure of toxic mine wastes. Coversoils with high coarse fragment content, referred to as "rock mulch", are occasionally used on steep slope reclamation to armor the ground surface against erosion. At the Golden Sunlight mine near Whitehall, Montana, reclamation is performed on slopes of 2:1 (45%) to reduce costs involved with grading large mine waste piles to a more gentle slope and to limit the area impacted by the mine. Special equipment is used to grade and seed the slopes. Coversoils with the "rock mulch" surface have been used on the steep slopes to protect against erosion (*Smith, 1996*). A study in Elko, Nevada, by *Leavitt et al., 2000,* demonstrated that the use of highly coarse coversoil may provide some slope stability up to the angle of repose of the materials used. Difficulty establishing vegetation on coarse coversoils limited the success of this approach. Fine textured coversoil provided for better plant establishment but proved to be highly erosive and unstable leading to mass movement of coversoils (*Leavitt et al., 2000*).

In steep native environments, slope aspect influences the species composition of plant communities. In the northern hemisphere, plant communities on north aspects tend to be more productive compared to those growing on the drier south facing aspect. The hot and dry conditions on south facing aspects often restrict plant communities to species capable of tolerating near drought conditions throughout portions of the growing season. The limited and sporadic vegetative cover of plant species growing on south aspects increases the likelihood of soil erosion.

Coversoil Properties

Coversoil properties including soil texture, rock fragment content, bulk density, water holding capacity, replacement depth, nutrient levels, soil organic matter, biological components, and trace element concentrations play extremely important roles in promoting long-term reclamation success. A literature review of these coversoil properties is detailed in the following sections.

Soil Texture, Rock Fragments, & Bulk Density

Coversoil texture largely determines the soil's ability to retain water and nutrients. Coarse textured soils with a high volume of rock fragments, minimal clay, and low organic matter levels possess very poor water and nutrient holding capacities. A high percentage of rock fragments reduces rooting volume, limits water holding capacity, and restricts nutrient storage. Excessive surface rock fragments may elevate ground surface temperatures hindering germination (*Baskin et al., 1998*). Sandy soils contain a high percentage of large pores for water movement. Since water storage occurs primarily in small pores, only limited amounts of plant available water can be stored in sandy soils. Rapid water infiltration of sandy soil may result in the leaching of plant available nutrients and drainage of water beyond plant rooting depths.

During periods of low precipitation, soil moisture may become extremely limited to below the point at which most plants can extract sufficient soil water, known as the permanent wilting point. Permanent wilting point usually occurs when the soil matric potential reaches 15 bars. The high matric potential restricts the soil's ability to transmit water and the plant's capacity to extract moisture leading to wilting, senescence, or death. Vegetation capable of surviving under drought conditions often does not provide adequate ground cover, leaving bare soil susceptible to weed invasion and erosion. Successful reclamation involves the application of coversoil capable of storing and providing sufficient soil moisture during the growing season to promote productive plant growth and establishment. Of course, soil moisture is linked to precipitation events, yet the soil must be capable of retaining essential amounts of soil moisture between growing season precipitation events to promote plant germination, establishment, and persistence of the species (*Bradshaw & Chadwick, 1980*). Unless a source of plant available water can be reached by plant roots beyond the surface soils, shallow and coarse textured soils (sand, loamy sand, and to a lesser degree sandy loam) in arid and semi-arid climates may not retain sufficient moisture to support robust vegetation (*Jones & Graham, 1993*).

High soil bulk density can limit plant growth through reduced germination and root penetration. A study by *Jones, 1983*, demonstrated that root penetration depended on the soil bulk density, clay + silt percentage, and soil moisture content. The critical bulk density was approximately 1.6 g/cm^3 for root penetration in soils with 70% clay + silt under optimal soil water conditions. Research by *Hanks & Thorp, 1956*, showed that as bulk density increased from normal to maximum compaction, seedling emergence decreased dramatically. An increase in surface crust strength due to compaction led to increased soil bulk density and decreased oxygen diffusion rates that inhibited germination. Surface compaction may intentionally be created on reclaimed areas to help prevent soil erosion prior to plant establishment by tracking the area with large equipment. Unfortunately, this compaction may often increase future soil erosion due to reduced plant productivity and cover.

Coversoil Depth

Coversoil depth should be sufficiently thick to provide an ample root zone for the reclaimed plant community. Average maximum plant rooting depths for various native grass species, as determined by a monolith study (*Weaver, 1958*) are shown in Table 1. The majority of these native grasses, generally require at least 1.22 meters (m) (4 ft) of suitable soil to attain maximum rooting depth. A study performed by *Coupland & Johnson, 1964*, in Saskatchewan, Canada indicated that various plant species require at least 1.22 m of suitable soil to facilitate natural root distribution. In most cases, greater than 50% of the root mass was located in the upper 15 cm of the soil profile. However, the deepest roots were determined to be highly important for water extraction during drought periods. In arid and semi-arid environments the maximum rooting depths shown in Table 1 may not always be obtained.

Table 1. Native grass species average maximum rooting depths (*Weaver, 1958*)

Native Grass Species	*Average Maximum Rooting Depth Depth Varies Based Upon Soil Type*	
Western wheatgrass (*Agropyron smithii*)	152 - 213 cm	(5 - 7 ft)
Needle & Thread (*Stipa comata*)	122 - 152 cm	(4 -5 ft)
Big bluestem (*Andropogon gerardi*)	122 - 152 cm	(4 - 5 ft)
Switchgrass (*Panicum virgatum*)	244 - 335 cm	(8 - 11 ft)
Canada wildrye (*Elymus canadensis*)	76.2 cm	(2.5 ft)
Little bluestem (*Andropogon scoparius*)	122 - 152 cm	(4 - 5 ft)
Needlegrass (*Stipa spartea*)	137 - 183 cm	(4.5 - 6 ft)
Sand dropseed (*Sporobolus cryptandrus*)	122 - 152 cm	(4 - 5 ft)
Side oats grama (*Bouteloua curtipendula*)	137 - 168 cm	(4.5 -5.5 ft)
Purple three awn (*Aristida purpurea*)	122 - 152 cm	(4 - 5 ft)

Near Lincoln, Nebraska, during times of extreme drought (1933 - 1940), plant death was found to be directly correlated with rooting depth (*Weaver et. al, 1935*). Shallow rooted species, unable to extract water from dry upper soil horizons, did not survive.

Power et. al., 1981, determined that the productivity of Alfalfa (*Medicago sativa*) and Crested wheatgrass (*Agropyron cristatum*) increased as suitable soil thickness increased from 90 - 150 cm (2.95 - 4.9 ft). The experiment consisted of soil wedge treatments placed over unsuitable sodic spoils. Generally, 90% of maximum yield was attained when a total of 90 cm (2.95 ft) of soil consisting of 70 cm (2.3 ft) of suitable subsoil plus 20 cm (0.65 ft) of topsoil covered the sodic spoils. Both Alfalfa and Crested wheatgrass were found to extract water at depths greater than the thickness of the soil wedge up to 150 cm (4.9 ft).

A study near Colstrip, Montana, (*Wyatt et al., 1980*) evaluated rooting depths of fifteen plant species on native soils, old mine spoils, and new mine spoils. The deepest rooting depth was recorded at 183 cm (6 ft) on suitable old mine spoils. Roots that extended below 76 cm (2.5 ft) totaled only 5% of the entire root biomass. These deeper roots may be essential for water uptake during drought conditions. The study indicated that an adequate plant-rooting zone requires a minimum 2 m (6.5 ft) of suitable soil, whether it is topsoil or acceptable substrate material. This study was performed on coal mining reclamation, yet rooting depths of similar plant species are not likely to greatly differ in hardrock mining reclamation situations.

In addition to coversoil requirements on coal mining reclamation, the upper four feet of substrate materials (upper 2.44 meters (8 ft) according to Montana statutes) must also meet suitability requirements that further support plant growth. Substrate materials at many hard rock mines can be toxic to plants and the environment. The substrate or hard rock mine waste often does not provide an adequate rooting medium. Plant roots, as a result, are often restricted to the coversoil layer applied during reclamation in hard rock mining areas.

Soil borrow resources can often be limited in hardrock mining areas, such as in the Butte area. Precious metal ore bodies are primarily located in igneous formations. Igneous rocks, including intrusive granites and extrusive volcanics, weather very slowly in semi-arid environments. Resulting soils are often coarse textured and/or contain abundant hard rock fragments. Locating sufficient amounts of good quality coversoil materials to provide a suitable plant rooting depth zone often becomes extremely difficult and expensive under these conditions. Shallow coversoils on many hard rock reclaimed areas restrict deep-rooted plant species especially if toxic substrate conditions exist. Vegetation restricted to a thin coversoil layer will rapidly deplete plant available nutrients and water requiring future inputs of fertilizer or organic matter to sustain adequate vegetative cover. Shallow, coarse textured coversoils, coupled with a semi-arid climate makes for extremely difficult growing conditions.

Nutrients, Organic Matter, & Biological Activity

Providing an adequate supply of plant nutrients is essential for achieving suitable vegetative productivity, maintaining ground cover, and ensuring the long-term survival of reclaimed plant communities. Vegetation on hardrock reclamation is often faced with limited nutrient conditions in coversoils from local borrow sources. Borrow materials used are often devoid of plant available nutrients, soil organic matter, and the biological community normally present in topsoil materials. Development of proper carbon and nitrogen cycling and the building of biological communities may require decades or centuries on some harsh sites (*Reeder & Sabey, 1987; Hook et al., 1995*), meanwhile plant growth can be dramatically suppressed. Oftentimes, fertilizer and organic amendments are applied during initial reclamation to establish vegetation and initiate the natural nutrient cycling processes. Initial fertilizer application may not be enough in many instances. Long-term fertilizer applications can be used to provide a continuous source of plant available nitrogen but the long-term management costs can be prohibitive. Excessive fertilization may also increase plant nutrient levels to a point where weed species are favored over the native grasses (*Morghan & Seastedt, 1999*). Rangeland plant species used for revegetation tend to require a low, steady supply of plant available nutrients and often do not benefit from excess nutrient concentrations. Once present, weed species may gain dominance by out competing native rangeland species for the most limiting resource (*Tilman, 1984*).

Studies of reclaimed lands have indicated that soil moisture can be the most limiting factor to vegetative growth, followed by plant available nitrogen. Plants extract more nitrogen from the soil than any other nutrient to promote growth and reproduction (*Reeder & Sabey, 1987*). Inputs of nitrogen to the soil in natural systems occur partly (approximately 28%) through atmospheric additions of $N0_3^-$ and NH_4^+ from precipitation, while the majority (approximately 72%) is added through biological fixation (*Foth & Ellis, 1996*). Biological nitrogen fixation supports plant growth and helps to develop proper carbon and nitrogen cycling. Sterile coversoil materials substituted for topsoil do not provide the biological soil component essential for nitrogen fixation. Long-term plant growth will inevitably suffer without continued nitrogen inputs through management practices involving organic amendment incorporation or nitrogen fertilization.

Coarse textured soils limit plant available water and nutrient retention. Even with an adequate biological community, lack of soil water will restrict microbial activity (*Burke, 1989*). As a result, nitrogen mineralization diminishes when soil water potential decreases to permanent wilting point and lower concentrations. Such dry soil conditions are not supportive to biological nitrogen fixation.

Legume establishment may alleviate plant available nitrogen deficiencies. Soil nitrogen fixation occurs through a symbiotic relationship between legumes and bacteria in the genus *Rhizobium*. Legumes supply the *Rhizobium* with a fixed carbon (phosphosynthate) and in return the bacteria supplies nitrogen as ammonium for use in legume cells. Unutilized nitrogen is excreted by the plant roots into the soil (*Foth & Ellis, 1996)*. Prior to planting in agricultural or reclamation situations, legume seeds are often inoculated with the proper *Rhizobium* species to ensure efficient nitrogen fixation. A report by *Sheehy, 1989,* suggests that a legume content of 20% cover in pastures creates optimum conditions for overall plant community productivity. According to *Reeder, 1990,* the amount of nitrogen added to soils by legumes may be a more effective means of establishing nutrient cycling than applying an equivalent amount of inorganic nitrogen fertilizer. The inorganic nitrogen fertilizer can be susceptible to both volatilization and leaching. Leaching especially occurs in coarse textured soils.

Legumes can be difficult to maintain if herbicides are broadcast applied for weed control. Broadleaf species are often targeted with herbicides, killing weeds and legumes alike. Spot spraying weeds can protect the majority of legumes, yet can be time intensive, costly, and does not effectively eliminate undetected weeds and weed seeds ready for germination.

Organic matter incorporation can provide biological components, an organic nitrogen source, and increase water retention for coarse textured coversoils. The mineralization of organic nitrogen from organic matter provides a long-term source of nitrogen available for plant uptake (*Schoenholtz et al., 1992*). According to a study by the *University of California, 1998,* the slow release of mineralized nitrogen from compost maintained low enough inorganic nitrogen levels to discourage the invasion of weed species. Organic matter incorporation (compost) combined with legume establishment during initial reclamation may help initiate nutrient cycling (*Prodgers, 1998*) providing a common sense substitute for long-term fertilizer applications.

<u>Climate</u>

The lack of precipitation is often the most important variable determining reclamation success in arid and semi-arid environments. Precipitation combined with temperature set the stage for seed germination and establishment of mature plants. Generally, the first growing season is most crucial in terms of predicting short to mid-term revegetation success. During the first growing season, hot and dry conditions can greatly limit seed germination and plant establishment. Harsh weather conditions that lead to revegetation failure do not necessarily have to exist for the entire growing season to dramatically effect plant establishment. The timing and patterns of precipitation are often more important than the overall amount of moisture received (*Ries & Svejcar, 1991*). Several weeks of hot and dry conditions during germination and seedling establishment can completely cripple revegetation efforts for the remainder of the year, even though total precipitation may be above average for the year.

Weather conditions in semi-arid environments are always questionable. Unfortunately, adverse weather cannot be manipulated to improve reclamation efforts. Climate limitations can be offset to some extent by using coversoil with good water retaining capacities and sufficient soil organic matter levels. Even ideal coversoil properties will not guarantee reclamation success during drought conditions. In some cases, irrigation can be applied to alleviate dry conditions and improve plant cover. While necessary in some instances, this approach is expensive and not a practical long-term solution for most reclamation situations. Water sources can often be limited in Montana's semi-arid regions. Even if water is available, the long-term irrigation costs may be prohibitive, likely exceeding the reclamation design and construction costs. In some instances, reclamation practices may include first year irrigation to improve plant establishment, but only if water is readily available and irrigation setup costs are low. Even with excellent plant establishment using first year irrigation, the fate of the plant community can be highly dependent upon future climatic conditions (*McLean & Wikeem, 1983*). If precipitation is inadequate and temperatures are excessive for extended periods of time, even well established vegetative cover may decline or fail due to restricted soil moisture.

Trace Elements

Phytotoxic conditions occur when trace elements in the soil reach levels that cause injury or death to plants. Many environmental factors influence the exact concentrations at which phytotoxicity begins. The form of trace elements present, solubility of metal and arsenic species, soil pH, soil moisture conditions, and the plant species growing on a site will all influence at what level injury occurs. Concentrations harmful to plants may be harmful to animals as well. Soil microorganisms and burrowing animals are likely to be most affected. Yet, other animals that feed on those animals or feed on plants growing in contaminated soil will also suffer injury. Humans are not immune. A short list of human ailments associated with chronic exposure to toxic trace element concentrations include numerous cancers, brain damage, nervous system defects, respiratory defects, and skin lesions.

Ironically, plants require minimal concentrations of trace elements as micronutrients. In many cases, plants are less tolerant of insufficient trace element concentrations than elevated concentrations (*Kabata-Pendias & Pendias, 1992*).

Laboratory Analyses & Trace Element Effects

Oftentimes, the choice of analytical methods for trace element detection is intended to mimic the trace element concentration a plant would likely extract from the soil. The selection of proper extraction solutions (EDTA, DTPA, ammonium acetate, water, buffered, unbuffered, etc.) representative of trace element uptake by plants under variable field conditions have been highly debated. As an alternative approach to extractable analyses, total soil trace element concentrations can be detected through strong acid digestion. Total trace element concentration represents the entire pool of a trace element in the soil, both soluble and insoluble.

The interaction between plants and trace elements can be highly complex. Analysis of extractable and total soil trace element concentrations might not adequately assess whether phytotoxic conditions are present. Several combined factors often lead to phytotoxic conditions. Trace elements interact with soil properties such as texture, soil pH, cation exchange capacity, soil organic matter, and nutrient levels, as well as microorganisms, invertebrates, and other elements at specific ratios to hinder plant growth (*Tyler et al., 1989*). A large number of experiments have been performed to determine exactly how elevated trace element concentrations affect a plant. According to *Kabata-Pendias & Pendias, 1992,* trace element effects have been recognized to alter plant cell membrane permeability, which limit water and essential nutrient uptake capabilities. Trace elements aggressively compete with various metabolites and major cations for exchange sites within plant cells. The trace elements tend to specifically target and occupy uptake sites for nitrogen and phosphate. Trace elements also react with phosphate groups and cellular energy groups ADP and ATP. These processes act upon and/or destroy the plant's ability to utilize nutrients and enzymes needed for survival. Trace elements can also behave differently within the soil according to electronegativity of divalent metals, solubility products of sulfides, stability of chelates, and metal bioavailability (*Kabata-Pendias & Pendias, 1992*). Visible symptoms of phytotoxicity in plants can be varied. Some typical symptoms include necrosis, chlorosis, brown spots on leaves and margins, abnormal twisted and gnarled root shape, and overall stunted plant growth. Specific trace element uptake and phytotoxic effects for arsenic, copper, lead, zinc, cadmium, and manganese are detailed below.

<u>Arsenic</u>

Elevated soil arsenic levels can be very phytotoxic to plants. Decreases of up to 90% in plant growth have been observed for cereal grain species at total soil concentrations of 1,000 mg/kg (*Kabata-Pendias & Pendias, 1992*). Total soil arsenic concentrations do not represent actual amounts of arsenic available to plants. Arsenic^{5+} is believed to be the most readily available form of arsenic for plant uptake. This form of arsenic can be passively transmitted to plants with water flow. Anion arsenic species behave differently in the soil than cation metal species. At high pH levels, arsenic can be highly soluble, whereas the majority of metal cations are soluble primarily at low pH levels. Arsenic poisoning can cause leaf wilting, deep red to violet discoloration of roots and leaves, depressed tillering, and wilting of new growth. Plant tissue concentrations of arsenic ranging from 1.1 to 5.4 ppm have been observed in healthy grasses growing in a semi-arid region in Russia. Accumulation of arsenic in plant tissue seldom reaches levels harmful to humans or grazing animals due to above ground growth reductions and plant death (*Adriano, 1986*). However, a related problem for grazing animals might be the consumption of contaminated dust on the surface of the plant.

Copper

Excess copper can cause plant tissue damage, depressed growth, poor seedling development, and reduced root development (*Tiller & Merry, 1981*). Phytotoxic copper concentrations can be highly variable and difficult to assess. Other elements, such as sulfates and oxides, within the soil form complex interactions with copper that can be either favorable or toxic to vegetative processes. The phytotoxicity of the complexes depends upon the elements involved and their associated concentrations (*Kabata-Pendias & Pendias, 1992).*

Lead

Phytotoxic levels of lead can cause leaves to turn dark green and/or wilt, stunt foliar growth, depress root growth, and discolor roots brown (*Kabata-Pendias & Pendias, 1992*). However, these effects are often only observed at high lead concentrations as soil lead is often unavailable to plant roots. Studies have shown that plants extract much less than 1% of the total soil lead concentration (*Wilson & Cline, 1966*). Plants can absorb large can absorb high concentrations of lead, near 300 ppm, often without showing phytotoxic effects (*Gough et al., 1979*). Lead uptake by plants is reported to be constant with changing soil lead concentrations. However, at very high soil lead concentrations, a critical level of lead in plant tissue may be reached (depending upon plant species) beyond which dramatic increases in lead uptake occur, leading to plant death (*Antonovics et al., 1971*). Elevated soil lead has been shown to have a large impact on soil microorganisms. Soil lead contamination can impair microbial activities needed for nutrient cycling and organic matter decomposition (*Tyler, 1976).*

Zinc

Elevated zinc concentrations in soil can cause depressed plant growth and chlorosis of new growth. Zinc is not considered to be highly phytotoxic and only select sensitive plant species (cereals and spinach) at various growth stages have shown effects of poisoning (*Davis, 1979*). Upper phytotoxic levels of zinc have been measured at 500 ppm in plant tissues, a fraction of total zinc soil concentration. Such high zinc concentrations in contaminated plant tissues are found primarily in plant roots and leaves. Cellular resistance to elevated zinc concentrations is not well understood, yet plants may have an internal tolerance mechanism which explains the high concentrations of zinc frequently found within healthy plants growing on contaminated areas (*Antonovics et al., 1971*).

Cadmium

Elevated levels of soil cadmium can lead to chlorosis, brown leaf margins, curled leaves, brown stunted roots, and reduced overall growth. Plants readily absorb soluble forms of soil cadmium. Different plant species have shown varying levels of cadmium tissue concentrations (10 - 100 ppm) when grown on the same soil (*Kabata-Pendias & Pendias, 1992*). Cadmium phytotoxicity generally occurs at much lower concentrations than copper, zinc, arsenic, or lead. Phytotoxic amounts of cadmium within plant tissues can range from 10 to 20 ppm depending on plant species (*Macnicol & Beckett, 1985*).

Manganese

Manganese uptake and translocation throughout a plant occurs in combination with passive water transport. The tolerance of plants to manganese is dependent upon the proper manganese to iron ratio within plant tissues. Specific ratios and effects differ greatly among plant species and growth stages (*Kabata-Pendias & Pendias,* 1992). Manganese phytotoxicity is most likely to occur in acid soils associated with aluminum toxicity. High soil manganese levels can cause chlorosis and necrotic lesions and spots on leaves, accumulation of MnO_2 in epidermal cells, drying of leaf tips, and stunted root and above ground biomass (*Kabata-Pendias & Pendias, 1992*). Tissue contents of 500 ppm have exhibited phytotoxic effects in some cereal crops, whereas tissue concentrations greater than 1000 ppm have been reported in healthy wheat crops (*Adriano, 1986*).

Indirect Trace Element Toxicity Effects

Soil biota harmed by toxic trace element concentrations can indirectly hinder plant growth. These indirect effects may be difficult to measure in terms of plant performance. Ideally, the assessment of phytotoxic conditions should consider all pathways of harm. Often, the effects of trace element contamination within the soil are misunderstood by only evaluating plant growth, and not the entire soil community.

Elevated trace element concentrations can pose harm to soil microorganisms and invertebrates, including insects and spiders (*Hopkin, 1986*). Negative impacts on these organisms may inhibit plant growth by reducing nutrient cycling, decomposition of organic materials, and soil respiration. Microorganisms utilize soil organic matter for nutrients and energy. Trace elements may be readily adsorbed to soil organic matter, increasing total trace element concentrations in high organic matter areas. A study performed on German soils contaminated with copper and zinc from nearby smelting processes indicated that microbial activity was eight times less near the smelter than the microbial activity in outlying, uncontaminated soils (*Tyler et al., 1989*). Nitrifying bacteria, such as *Azotobacter*, and mycorrhizal fungi are especially sensitive to elevated trace element concentrations. Spore germination and hyphal extension rates into leguminous plants can be decreased by elevated trace element concentrations, reducing or eliminating nitrification by these plants (*Hepper & Smith, 1976*). Microbial decomposition rates can also decreased by elevated trace element concentrations. Considerable litter layer increases have been reported near lead smelters in Missouri, Ontario, and England due to reduced microbial decomposition (*Coughtrey et. al., 1979*). Excess, non-decomposed plant litter layers were identified at distances up to 15 km from a lead smelter in Ontario (*Freedman & Hutchinson, 1980*). Decreases in decomposition rate, phosphatase activity, and phosphorus mineralization were observed on forest soils located near metal processing industries, specifically copper and zinc processing (*Tyler, 1976*).

Soil invertebrates, especially earthworms, are highly susceptible to trace element contamination. The continual feeding on contaminated soils concentrates trace elements in the digestive system, eventually killing the organism. Studies have shown that total soil trace element concentrations approximately twenty times higher than background concentrations reduced earthworm populations dramatically (*Tyler et al., 1989*). Insects and spiders that feed on other invertebrates are susceptible to trace element poisoning by consuming prey concentrated with trace elements. High trace element concentrations have been observed in spiders (*Dysdera*), which have fed on soil invertebrates contaminated with trace elements (*Hopkin, 1986*).

Reclamation Challenges in Butte, Montana

ARCO began reclamation efforts in Butte, Montana during the early 1980's. These efforts continue still today. Vegetation on various reclaimed areas currently does not meet 30% live plant cover standards (*Prodgers, 1995*) based on point intercept measurements (*Daubenmire, 1968*) accepted by the local Butte Silver-Bow county government. Coarse textured sandy loams weathered from decomposed granite were used for the majority of reclamation prior to 1997. These coarse textured coversoils frequently possess poor water holding capacity and are deficient in plant available nutrients, soil organic matter, and soil microorganisms essential for sustaining vegetation.

Phytotoxic mine waste lies directly beneath an approximate 5 cm thick lime rock barrier and the coversoil cap on the majority of Butte reclaimed areas. The low pH and high trace element concentrations of the mine waste create highly unsuitable conditions for plant growth.

Plants growing on the reclaimed areas are restricted solely to the coversoil depth placed during initial reclamation activities. The hard and dense lime rock barrier that separates the mine waste from coversoil materials tends to restrict root penetration to greater depths.

The EPA requirements for Butte reclamation specify that coversoil depth must be at least 46 cm (18 in) (*AERL, 1999*). Various reclaimed areas contain considerably less coversoil than the required amount. Shallow coversoils greatly limit the available pool of water and nutrients for plant growth. Plants can rapidly deplete available nutrients and soil water within a 46 cm coversoil thickness. In native, semi-arid environments, plant roots (depending upon species) may extend greater than 1.8 m to compensate for water shortages during drought conditions. As mentioned earlier for coal mining reclamation, the salvaged soil resource is placed over at least 1.2 m of suitable substrate materials to promote long-term vegetative growth. In comparison with coal mining reclamation standards and many undisturbed native environments, even the deepest coversoil on Butte reclamation is limiting to root penetration and long-term plant productivity because substrate materials are either phytotoxic or unsuitable for plant growth.

Many reclaimed areas in Butte have slopes nearing 3:1, or 33%, on south facing aspects. Butte's semi-arid climate receives 30.5 to 35.6 cm (12 to 14 in) of precipitation annually (*National Climatic Data Center, 1990*). The combination of slope, hot and dry south facing aspects, low annual moisture, and shallow coversoils with depleted nutrient concentrations and limited plant available water holding capacity hinder the establishment and survival of seeded vegetation. Reclaimed sites with poor vegetative growth may become susceptible to weed invasion and excessive coversoil erosion, possibly requiring complete reconstruction of the coversoil cap.

Changes have been made in reclamation practices during the past several years (1997 – present) that are improving vegetative cover on newly reclaimed Butte sites. Coversoil materials consisting of the coarse decomposed granite are no longer used as frequently. Tertiary fill from the nearby landfill in Rocker, Montana, has become the primary coversoil source. The loamy tertiary fill material contains a higher percentage of clay and silt than decomposed granite (*Prodgers, 1998*), capable of retaining higher concentrations of water and nutrients. Initial reclamation construction on many sites now includes cattle manure incorporation to improve soil organic matter percentages, increase nitrogen levels, and supply the biological components needed for establishing vegetation.

Approximately 170 ha (420 acres) of mine waste and disturbed areas have been reclaimed in Butte (actual reclaimed acreage is highly debatable depending on definition of reclamation and reclamation success). Approximately 40% to 50% of the total area has been reclaimed with coarse textured decomposed granite coversoils. Reclamation evaluations performed by the EPA and Bighorn Environmental on the reclamation performed during completed prior to 1997 have noted a decline in vegetative cover and increased erosion on numerous sites. Many of these reclaimed sites will require extensive maintenance and/or additional applications of coversoil to promote sustainable vegetation with greater than the accepted Butte-Silver Bow County criterion of 30% total live plant canopy cover based on the point intercept method (*Daubenmire, 1968*).

CHAPTER 2

PHASE I - INTRODUCTION

Reclamation in Butte, Montana, was evaluated to determine if relationships existed between coversoil properties and the current success levels in the vegetative cover of reclaimed sites. The Phase I assessment included the investigation of factors that may be contributing to satisfactory or poor vegetative conditions on Butte reclaimed areas. Vegetative declines apparent on various reclaimed sites may be attributed to a variety of factors such as coarse textured coversoil, limited water and nutrients, elevated trace element concentrations, and low pH (*Munshower & Neuman, 1992, Troutman, 1997*). Phase I was performed to assess specific causes of vegetative declines on Butte reclamation. Effective reclamation alternatives cannot be established if current problems are not clearly understood. Reclaimed sites rated from unsuccessful to successful based upon vegetative cover were studied to identify trends that may explain specific causes of vegetative declines. Definitions for Phase I reclamation success categories are provided in subsequent sections of this thesis.

Reclamation Specifications

The Environmental Protection Agency (EPA) general specifications for past and current Butte reclamation, outlined by "Butte Hill Revegetation Specifications" in the Final Response Action Design Report for the Alice Dump, March 18, 1999, (*AERL, 1999*) stipulate that all mine waste be removed and/or recontoured to slopes of 3:1 or less. The contoured mine waste must be capped with a 5 cm (2 in) lime rock layer or 785 metric tons of lime rock per hectare (350 tons lime rock/acre) and a minimum 46 cm (18 in) of coversoil to protect human health and the environment. Coversoil materials must meet certain physical and chemical requirements, explained in detail in later sections. Reclaimed sites are seeded with a suitable seed mixture, straw mulched at 4.5 metric tons per hectare (2 tons/acre), and fertilized with an appropriate chemical fertilizer. Fall seeding has been performed on the majority of past reclamation. An example of a typical reclaimed cap is shown in Figure 3.

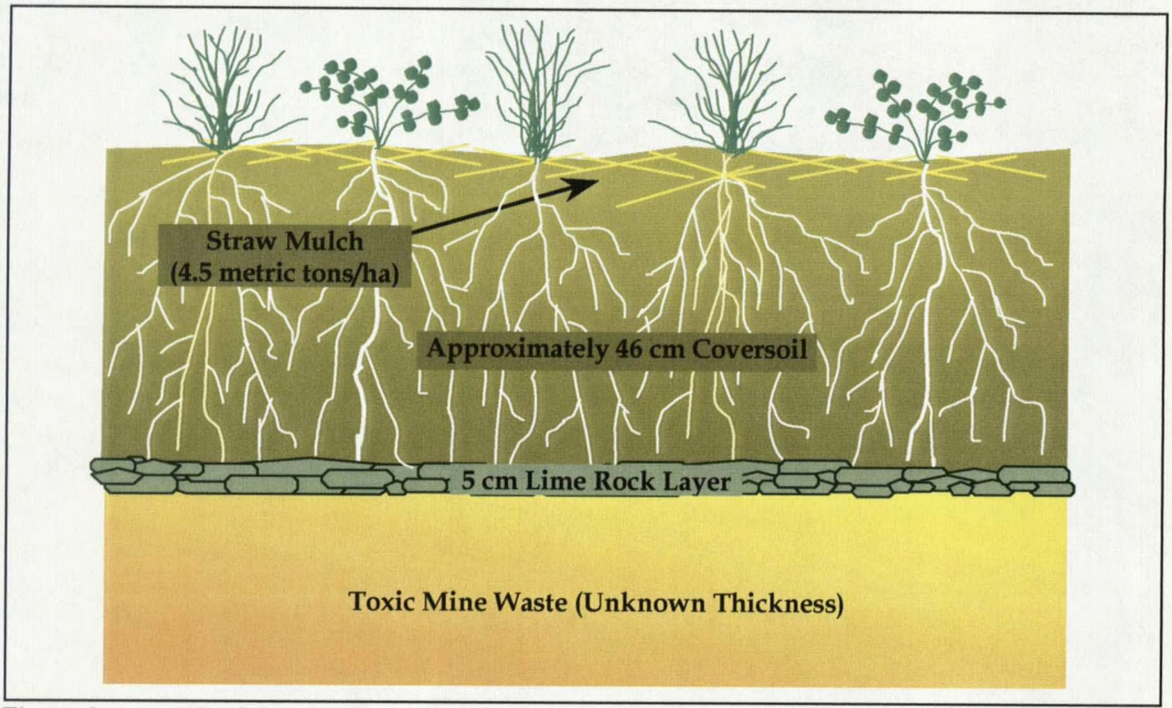


Figure 3. Reclaimed cap construction outlined in the "Butte Hill Revegetation Specifications" in the Final Response Action Design Report for the Alice Dump, March 18, 1999 (*AERL, 1999*) stipulate that at least 46 cm (18 in) of coversoil and a 5 cm (2 in) lime rock layer or 785 metric tons lime rock/ha (350 tons/acre) be placed over mine waste.

It is perceived, the regulatory agencies believe that reclamation adhering to the above specifications will effectively cap mine waste and maintain long-term sustainable vegetation (*AERL, 1999*) until other land use alternatives are considered. Any variations from these reclamation specifications were based upon individual Time Critical Removal Action (TCRA) guidelines provided at the time of reclamation. Prior to EPA involvement in the early 1980's, a portion of Butte reclamation was performed as a voluntary action by ARCO. The Abandoned Mined Lands Bureau and Butte-Silver Bow County also performed mine waste removal and attempted revegetation on numerous sites in the early 1980's (*MSE, 1992*).

Vegetative Declines

Coversoil applied during initial reclamation construction is expected to effectively cap mine waste areas for many decades. The establishment of vegetation is essential for providing coversoil stability. Vegetative cover protects the coversoil from wind and water erosion by minimizing areas of bare ground, reducing surface water runoff velocity, and by increasing infiltration. Loss of vegetative cover can lead to elevated coversoil erosion, which may eventually re-expose toxic mine waste. Storm events in Butte can readily erode and carry the exposed mine waste into city streets, residential property, and city storm drains. Uptown Butte city storm drains empty into Silver Bow Creek, often lowering pH and elevating trace element concentrations in the stream.

In order to assess the condition of various reclaimed areas and to identify reclamation problem areas involving exposed mine waste, the EPA evaluated Butte reclaimed areas twice in the 1990's. The evaluations were developed in cooperation with the Montana State University Reclamation Research Unit in 1992. These evaluations, performed in 1992 and 1996, assessed reclamation characteristics including various vegetative properties, erosion, signs of disturbance, and mass instability (*Munshower & Neuman, 1992, Troutman, 1997*). The evaluations provided information of initial vegetative trends on various reclaimed areas. Plant canopy cover data gathered from these evaluations are shown in the graph indicating plant cover trends from initial seeding dates (1988 – 1991) to 1996 on various reclaimed areas (Figure 4).

The reclaimed sites were grouped according to plant canopy cover values into successful, moderately successful, and unsuccessful reclamation categories. Four out of six reclaimed areas with excellent initial plant establishment in 1992 maintained successful vegetative cover through 1996. Two sites with excellent initial establishment and plant cover in 1992 declined to unsuccessful conditions by 1996.

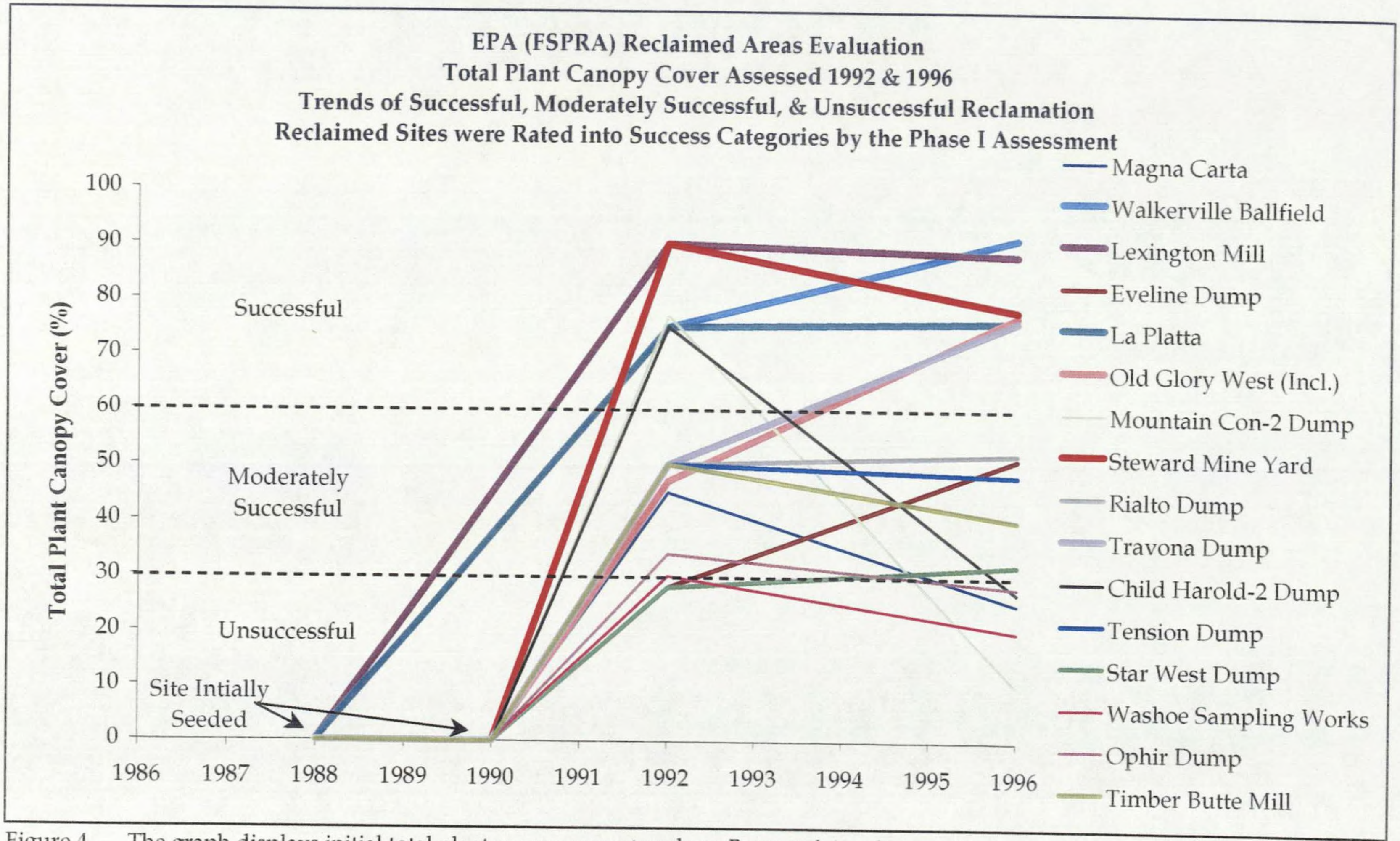


Figure 4. The graph displays initial total plant canopy cover trends on Butte reclaimed areas. Plant canopy cover values were determined according to visual estimates performed by evaluation officials. These reclaimed sites have been categorized by the Phase I assessment into success groups based upon the estimated plant canopy cover values. Successful reclaimed sites contain >60% canopy cover, moderately successful sites range from 30 to 60% cover, and unsuccessful sites contain <30% canopy cover.

On reclaimed areas where initial establishment was poor in 1992, vegetation was not able to achieve successful vegetative cover by 1996. The evaluations indicate that without excellent initial plant establishment during the first growing season, vegetation will not likely achieve future successful canopy cover values.

Plant reproduction is essential for promoting long-term vegetative cover and sustainability on reclaimed areas. Even on successfully vegetated sites, limited vegetative reproduction will lead to future declines in vegetative cover. The 1996 evaluation generally indicated the reproduction of few to common young plants on the reclaimed areas assessed. It should be noted that these EPA evaluations were performed on a relatively short time span following initial site seeding. *Prodgers, 1998,* indicates that conditions for plant regeneration on Butte reclaimed sites will become considerably worse in comparison with conditions existing during initial seeding.

As mentioned earlier, poor establishment and declines in vegetative cover may be attributed to a variety of factors. This Phase I assessment investigated coversoil properties including texture, coarse fragment percentage, depth, trace element concentrations, nutrient status, and soil organic matter percentages. Weather conditions during the first growing season were assessed to determine if poor initial establishment may have resulted in current vegetative failure on many sites. A better understanding of the causes of vegetative failure will provide an important first step towards reversing the decline of plant productivity and canopy cover on various reclaimed sites.

Phase I - Methods & Materials

Phase I Assessment - Reclaimed Area Selection

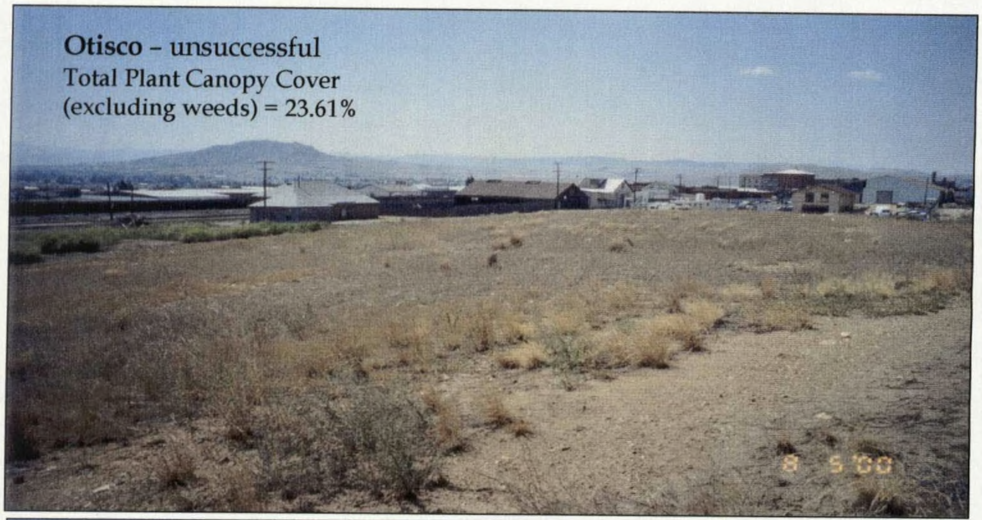
More than a hundred sites have been reclaimed in Butte, Montana to date. The assessment of all reclaimed areas was beyond the scope and budget for this project. Therefore, fourteen sites, perceived to be representative of the majority of Butte reclamation performed in the 1980's to the early 1990's, were selected for the Phase I assessment. These fourteen reclaimed areas were chosen based on the EPA evaluations performed by the MSU Reclamation Research Unit in 1992 and 1996. In addition, plant canopy cover, productivity, and available soils data reviewed in *Prodgers, 1998*, and *Keammerer, 1992*, influenced reclaimed site selection for Phase I. Additional site variables obtained from personal observations and the ARCO reclaimed area database such as slope, aspect, source and depth of borrow material, institutional controls, and original seed mixture were considered during the selection process.

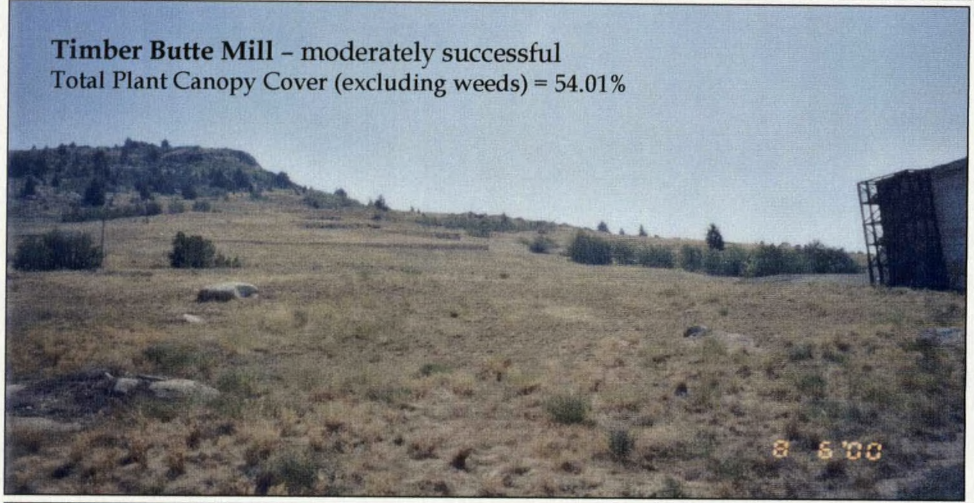
The fourteen sites (Table 2) selected represent examples of successful, moderately successful, and unsuccessful reclamation as well as the two common coversoil materials used for past reclamation (1982 – 1997) in Butte, Montana.

Table 2. Fourteen Butte, Montana reclaimed areas selected for Phase I assessment. Coversoil type used is indicated in parenthesis following site name.

Successful Sites	*Moderately Successful*	*Unsuccessful Sites*
Walkerville Ballfield (Ryan)	Timber Butte Mill (Other)	Washoe Sampling Works (I-90)
Lexington Mill (Ryan)	Travona Dump (I-90)	Star West Dump (I-90)
Late Acquisition (Other)	Original Mine Yard (Ryan)	Otisco (Other)
Steward Mine Yard (Ryan)	National (Ryan)	Poulin (Ryan)
Tension (Other)	---	Anselmo Mine Yard (Ryan)

These reclaimed areas were grouped into success categories in this Phase I assessment based upon data collected by the EPA, Keammerer, and Prodgers. Figure 5 illustrates examples of successful, moderately successful, and unsuccessful reclamation.





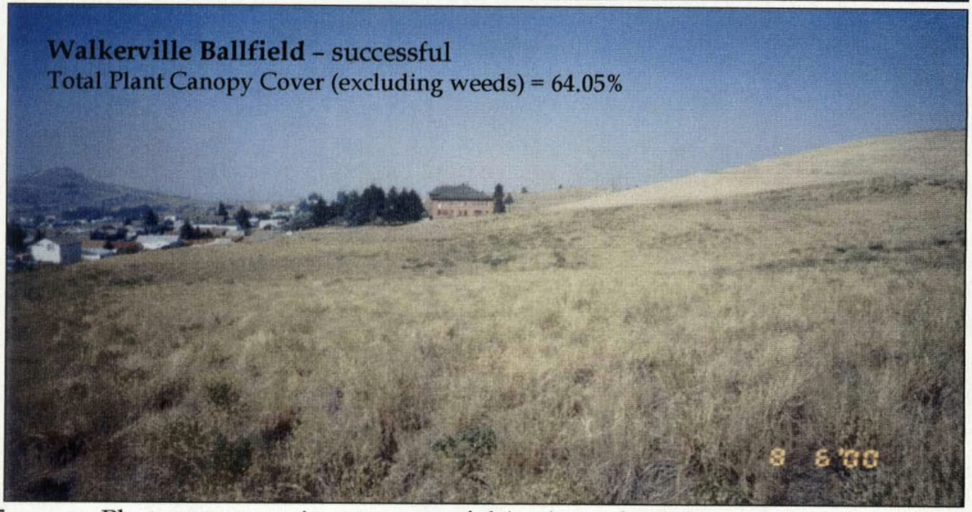


Figure 5. Photos representing unsuccessful (top), moderately successful (middle), and successful (bottom) reclaimed Butte sites based on vegetative cover. The photos display vegetative conditions as of August 2000. Plant canopy cover measurements were collected according to *Daubenmire 1959*.

The majority of reclamation prior to 1997 was performed with coversoils from either the Ryan or I-90 borrow sources. Other coversoil borrow sources were used on selected reclaimed sites. The Ryan borrow site is located just north of the town of Walkerville at the top of the Butte hill. This borrow site was abandoned in the mid 1990's due to reported cases of elevated trace element concentrations. Borrow material from the Ryan site has a gravelly, coarse sandy loam texture that averages 12% clay and 15% coarse fragments by volume. The I-90 borrow source is located southwest of Butte near interstate I-90. This material is very gravelly with a loamy coarse sand texture with an average 8% clay and 36% coarse fragments by volume. Coversoil physical properties for these two borrow source materials were determined by the Phase I assessment. Photos of the fourteen reclaimed areas including brief summarized data are also included in Appendix A. The photos display site conditions as of August 2000.

Field Data Collection

Soil samples were collected from the fourteen reclaimed areas in Butte (Table 2) on May 1, 1999. Plant canopy cover measurements were collected the following year on August 5 - 6, 2000, to correlate coversoil data with current plant canopy cover conditions.

Soil Sampling

Soils were sampled at three locations representative of vegetative conditions within each reclaimed area on May 1, 1999. Soil pits were dug to the lime rock barrier between the coversoil and underlying mine waste. Two soil samples were collected from each soil pit. Surface samples were collected from the 0 - 10 cm (0 - 4 in) coversoil depth increment and subsoil samples from 10 - 40 cm (4 - 16 in). Subsoil sampling in coversoils shallower than 40 cm was performed between 10 cm and the lime rock barrier. A 10% hydrochloric acid solution was used to detect the presence of the lime rock material. Care was taken not to mix lime rock material with the subsoil sample. The surface and subsoil samples were collected to identify differences within the reclaimed cap possibly caused by the upward migration of low pH water and trace elements through the lime rock barrier from the underlying toxic mine waste. Surface samples from all three pits were composited by thoroughly mixing the soils in a stainless steel bowl. The same composite procedure was followed for the subsoil samples.

Approximately 1,500 grams of soil were obtained for both the surface and subsoil samples from each reclaimed site. The mixing bowl and all sampling equipment were washed with Alconox soap and deionized water between mixing batches to prevent cross contamination of samples. The two composite samples from each reclaimed area were transferred to labeled zip-lock bags and were stored in coolers for transfer to the laboratory. A total of 28 soil samples were collected and submitted for laboratory analyses. During the soil sampling, field observations including slope steepness, aspect, and coversoil depth were recorded at each sample site.

Plant Canopy Cover Measurements

On August 5 and 6, 2000, measurements (*Daubenmire, 1959*) of plant canopy cover were recorded on the fourteen reclaimed areas. Daubenmire measurements were collected within a 1.0 x 0.5 meter (m) frame for canopy cover by species, surface litter, bareground, moss and lichen, and surface coarse fragments. Individual plant species values measured within each frame were combined to obtain total plant canopy cover. Twenty frames of cover data were collected from three 40 m transects on each reclaimed area for a total of 60 frames per reclaimed site. Individual reclaimed areas were carefully inspected to determine representative locations for transect placement. Transects were not oriented in a particular or consistent manner, but were placed to best capture the overall vegetative cover of each reclaimed area.

Laboratory Analyses

Soil analyses were performed at the Montana State University (MSU) Soils Laboratory. Soil samples were dried at 105^0 Celsius (C) for 48 hours or until consistent dry weight was obtained. The dried samples were disaggregated and sieved to obtain the less than 2-millimeter (mm) soil fraction for analyses. All particles larger than 2 mm were recorded as coarse fragments. The following parameters were analyzed for soil samples collected on May 1, 1999. Analytic procedures are briefly described for each parameter (*Page et. al., 1982*).

- *Total trace elements (Cu, Fe, Zn, Pb, As, Cd, and Mn)* were extracted using hydrofluoric acid and other mixed acids at a 1:100 ratio of soil to solution. The extract solution was analyzed for total trace elements with Inductively Coupled Plasma Spectrometry (ICP) analysis.

- *Unbuffered DPTA extractable trace elements (Cu, Fe, Pb, As, Cd, Al, Cr, and Mn)* were extracted with an unbuffered DTPA extract for approximately two hours. The extract solution was analyzed for trace elements using ICP analysis.

- *pH* was measured by mixing soil and water in a 1:1 slurry. The pH of the slurry was measured with a pH electrode.

- *Exchangeable acidity of Al^{3+} and H^+* was determined by filtering a 10 gram (g) soil sample with 25 milliliter (ml) of KCl solution through a Buchner funnel fitted with filter paper. The filtered solution was titrated with a NaOH solution until a clear color change endpoint was visually observed.

- *Cation exchange capacity (CEC)* was determined by saturating cation exchange sites with barium choride followed by mixing with $MgSO_4$ to react and replace barium with magnesium. The loss of magnesium from the reactant solution $MgSO_4$ was detected with Advanced Atomic Spectrometry (AAS). The magnesium loss was equal to CEC.

- *Electrical conductivity (EC)* was measured by mixing soil and water in a 1:1 slurry. The slurry was measured with an EC electrode. The EC and pH were measured simultaneously for each slurry sample.

- *Nitrate (NO_3^-) and ammonium (NH_4^+)* were detected by saturating soil with KCl in a 1:5 ratio for 30 minutes. The solution was decanted and filtered. The filtrate was analyzed colorimetrically with the auto-analyzer (AAII). Nitrates were observed using the automated cadmium reduction method and ammonium with the automated phenate method.

- *Total inorganic nitrogen* was analyzed with the Total Kjedahl Nitrogen (TKN) method and LECO total nitrogen procedures. TKN was determined by digesting 2 g soil with catalysts (potassium sulfate and hydrogen sulfate) and heating for 1 hour at 425^0 C. Total inorganic nitrogen was determined by a titration procedure with hydrogen sulfate to a color change endpoint. LECO total nitrogen methods were followed according to manufacturer specifications from LECO.

- *Olsen's phosphorus (P)* was determined by mixing soil and a 0.5 molar (M) solution of sodium bicarbonate in a 1:20 ratio for 30 minutes. A pH of 8.5 was obtained through this process. The solution was extracted and measured on the colorimeter.

- *Extractable potassium (K)* was detected at a neutral pH of 7 using a 1.0 M solution of ammonium acetate. The soil was saturated for 30 minutes followed by extraction and filtration. The filtrate was analyzed with AAS.

- *Organic matter* was detected using LECO total carbon procedures. Methods were followed according to manufacturer specifications from LECO. Inorganic carbon was tested for and subtracted from the total carbon concentration to obtain the correct amount of organic carbon. Organic matter was calculated by multiplying total organic carbon by a correction factor of 1.72.

- *Particle size distribution* was determined with the bouyoucos hydrometer method (*Bouyoucos, 1962*). A 50 g sub-sample of the less than 2 mm soil fraction was placed in a dispersing cup with deionized water and 5 ml of hexametaphosphate. The solution was thoroughly mixed on a shaker rack. The contents were then placed in a cylinder adding deionized water to attain the proper volume. The soil solution was vigorously stirred and allowed to settle while collecting hydrometer measurements at 40 seconds, 4 minutes, and 2 hours to obtain the sand, silt, and clay fractions respectively.

- *Saturation percentage* was determined by completely saturating a 50g sub-sample of soil with deionized water. The sample was dried at 105^0 C until constant weight was achieved. The weight of water divided by the dry weight of soil equaled the saturation percentage.

- *Field capacity at 1/3 bar and permanent wilting point at 15 bars* of disturbed soil samples were determined using a pressure plate extractor. Water Holding Capacity (WHC) was determined by saturating sub-samples of soil with deionized water and pressurizing them at 1/3 bar and 15 bars for several days or until soil/water equilibrium was achieved. The weight of remaining water in each sample was divided by soil sample dry weight at 35^0 C.

- *Bulk density* was determined by collecting intact soil peds. The peds were weighed, coated with paraffin wax, and immersed in a volumetric cylinder containing water. Bulk density was calculated by dividing the soil ped weight by the volume of displaced water.

The quality and quantity of data obtained through laboratory analyses were checked with data quality objectives. Qualitative and quantitative statements were defined for each procedure to ensure the accuracy and precision of analytical data was adequate to thoroughly assess coversoil properties.

Statistical Analyses

Total live plant canopy cover has generally been used in Butte to determine if reclamation currently meets suitability standards, requires maintenance, or is in need of complete reconstruction. During the last decade, a number of individuals with the EPA, Butte-Silver Bow County, and ARCO have measured total canopy cover values to assess reclamation success. Total plant canopy cover data collected by Prodgers 1995 through 1998 and Keammerer 1989 through 1990 were correlated with coversoil data to detect possible past trends in vegetative cover related to reclamation success or failures. Information contained in these data sets does not completely assess all fourteen sites evaluated under this Phase I study. Total canopy cover data collected by these individuals were obtained using both Point-intercept and Daubenmire methods. As a result, the data sets needed to be treated separately, limiting statistical analyses. For these reasons, only the total plant canopy cover data collected for the Phase I assessment in August 2000 were used for statistical correlations.

Descriptive statistics and histograms for each soil property were examined to determine appropriate statistical approaches for relating coversoil data with total plant canopy cover. One-way analysis of variance and linear regression were used to analyze the relationships of coversoil properties to plant canopy cover on the reclaimed sites. Descriptive statistics are presented for each soil variable to show the range of soil properties encountered in the reclamation. Significant differences would not be expected for variables that have a narrow range of value or that are limiting across all treatments. Histograms were plotted to determine the distribution of the data. One-way analysis of variance (ANOVA) mean comparison tests (Least Significant Difference) in *SAS v8* were used to detect significant differences in plant canopy cover for non-uniformly distributed coversoil data sets that contained obvious class breaks.

Simple linear and multiple linear regressions in *Microsoft Excel 2000* and *SPlus 2000* were also used to correlate coversoil data sets (independent variables) with plant canopy cover data (dependent variables). Regression significance was checked with p-values calculated from an ANOVA in *SPlus 2000*. P-values represent the probability of exceeding the value of the test statistic under the null hypothesis condition that no significant differences were present. The adequacy of the linear regression analysis assumptions were checked by observing the normal quantile-quantile plot of residuals for each regression performed in *SPlus 2000*.

Phase I - Results & Discussion

Current Reclamation Conditions

Total plant canopy cover data were collected August 2000 to assess the current vegetative conditions on the fourteen reclaimed areas. These reclaimed area (originally grouped into categories of successful, moderately successful, and unsuccessful reclamation according to 1992 and 1996 EPA evaluation data) were reclassified based upon the plant canopy cover data collected during the Phase I assessment in August 2000. Table 3 displays the fourteen reclaimed areas evaluated, their current reclamation condition, total plant canopy cover, desirable plant canopy cover, and undesirable plant canopy cover values. Desirable plant cover contains mostly perennial, non-invasive grass and forb species that effectively prevent soil erosion. These species may be native or introduced. Undesirable plant cover contains various annual, biennial, and perennial weed species that contribute minimal erosion protection and often deteriorate overall plant community health. Individual species canopy cover and ground cover data including litter, coarse fragments, bareground, and moss and lichen coverage measured on the fourteen reclaimed areas are included in Appendix B.

Successful reclaimed areas contain greater than 60% total and desirable plant canopy cover. Moderately successful sites contain 60 to 45% total and desirable plant canopy cover. Poor sites contain either less than 45% total plant cover or less than 45% desirable plant cover.

Table 3. Reclamation success category and total, desirable, and undesirable plant canopy cover values measured on the fourteen reclaimed areas in August 2000. Reclaimed sites have been reclassified into success categories based upon the Phase I canopy cover measurements collected August 2000.

Reclaimed Area	*Reclamation Success*	*Total Plant Canopy Cover %*	*Desirable Plant Canopy Cover %*	*Undesirable Plant Canopy Cover %*
Lexington Mill	Successful	80.45	79.80	0.65
Late Acquisition	Successful	76.35	76.35	0.00
Steward Mine Yard	Successful	77.15	76.30	0.85
Walkerville Ballfield	Successful	66.25	64.05	2.20
Travona	Moderately Successful	61.70	58.90	2.80
Original	Moderately Successful	62.20	58.15	4.05
National	Moderately Successful	56.32	56.17	0.16
Timber Butte Mill *	Moderately Successful	61.61	54.01	7.60
Tension	Moderately Successful	57.06	53.61	3.46
Star West Dump	Moderately Successful	51.35	48.40	2.95
Washoe Sampling Works *	Unsuccessful	46.87	41.76	5.12
Poulin Waste Dump *	Unsuccessful	37.55	28.20	9.35
Otisco *	Unsuccessful	53.21	23.61	29.61
Anselmo Mine Yard *	Unsuccessful	33.00	16.80	16.20

* Reclaimed area with undesirable plant cover comprising > 10% of the total live plant canopy cover.

All reclaimed areas classified as unsuccessful reclamation contain a high percentage of undesirable plant canopy cover that comprises greater than 10% of the reclaimed area's total plant canopy cover. These reclamation success category criteria differ from those shown in Figure 4 due to the different techniques used for plant cover measurements. Visual estimates of total plant canopy cover are shown in Figure 4. In the Phase I assessment, individual species canopy cover values were measured with Daubenmire methods (*Daubenmire, 1959*). Individual species measurements in the Phase I provided total plant canopy cover, and the amount desirable species and undesirable species present. Several reclaimed areas in Table 3 have changed success categories from those shown in Table 2 based upon plant canopy cover data collected in August 2000. The Tension has declined from successful to moderately successful and the Star West Dump has improved slightly from unsuccessful to moderately successful.

Species richness values for each reclaimed area indicate that sites with a high number of species generally have moderate to poor total canopy cover because a large percentage of the species are undesirable. A linear regression equation (total canopy cover = -2.66 x species richness + 86.44) with an $r^2 = 0.65$ and a significance value of $p < 0.0005$, predicts that a 95% chance exists that total plant canopy cover will be greater than 60% if there are less than six species present. Crested wheatgrass (*Agropyron cristatum*), Thickspike wheatgrass (*Agropyron dasystachyum*), Alfalfa (*Medicago sativa*), and Sheep fescue (*Festuca ovina*) were generally measured in the plant communities of successful reclamation with fewer than six species.

Summary Statistics for Coversoil Data

Coversoil samples were collected from the fourteen reclaimed areas May 1999. A range of soil properties were analyzed to determine the suitability of coversoil to support vegetation with greater than 60% total and desirable plant canopy cover. Coversoil data have been evaluated according to criteria provided by the Montana State University Reclamation Research Unit and "Butte Hill Revegetation Specifications" from the March 18, 1999, Final Response Action Report for the Alice Dump (*AERL, 1999*). Coversoil data not addressed by the revegetation specifications have been checked against recommended literature values. Summary statistics for coversoil physical properties, coversoil chemical properties, and trace element concentrations are displayed in Tables 4 through 6 respectively.

"Butte Hill Revegetation Specifications" state that coversoil materials must be applied at a minimum thickness of 46 cm (18 in) unless otherwise specified by the EPA. The average coversoil depth sampled the fourteen reclaimed areas was 41.12 cm (16.2 in), approximately 5 cm (2 in) less than the 46 cm requirement. Nine out of the fourteen sites assessed contain coversoil depths less than 46 cm. The shallowest coversoil depth was measured at 16.09 cm (6.33 in).

Table 4. Summary statistics of average physical properties measured for coversoils on the fourteen reclaimed sites.

Coversoil Physical Properties	*Mean*	*Max.*	*Min.*	*Std. Dev.*
Coversoil Depth (cm)	41.12	62.65	16.09	17.07
Coarse Fragments Vol. %	20.73	39.09	12.27	8.22
Bulk Density (g/cm^3)	1.68	1.83	1.60	0.07
Sand %	71.75	79.00	60.00	5.38
Silt %	16.46	22.00	4.00	3.54
Clay %	11.79	18.00	5.00	3.42
Vol. % H_2O at Saturation (0 Bar)	31.23	42.51	17.22	8.13
Vol. % H_2O at Field Capacity (1/3 Bar)	13.71	22.08	5.70	4.95
Vol. % H_2O at Permanent Wilting Point (15 Bars)	7.10	11.43	2.70	2.67
Plant Available Water Holding Capacity (Vol.-%)	6.61	10.77	3.00	2.54

Other investigators, including Keammerer and Prodgers, have noted a range of coversoil depths from 23 to 48 cm (9 to 19 in) with an average coversoil depth of 32.26 cm (12.7 in) on various Butte reclaimed sites as summarized by *Prodgers, 1994.*

Specifications state that coversoil coarse fragment percentages must not exceed 45% by volume. The average coarse fragment content by volume for the fourteen reclaimed areas was measured at 20.73% with a maximum of 39.09%. Reclaimed area coversoil bulk density values were often increased on sites with high coarse fragment content. The majority of Butte coversoils sampled classify as coarse sandy loams with the exception of a several loamy coarse sands. The EPA deems sandy loam texture as suitable while loamy sand is considered acceptable in only select cases. In addition, the revegetation specifications state that coversoils must retain greater than 25% and less than 85% water by volume at complete saturation. Four of the reclaimed area coversoils sampled retain less than 25% volumetric water at complete saturation.

Coversoil pH and EC falls within the acceptable range of 5.5 to 8.5 and less than 4 mmhos/cm respectively on all reclaimed areas sampled. The EPA revegetation specifications do not provide specific stipulations for suitable plant available nutrient concentrations, soil organic matter, or carbon to nitrogen ratios in coversoils. According to *Jacobsen, 2001,* plant available nitrogen less than 17 mg/kg, phosphorus less than 4 mg/kg, and potassium less than 75 mg/kg are considered to be very low. All reclaimed areas sampled have very low plant available nitrogen concentrations. The maximum and average plant available nitrogen concentrations were analyzed at 9.50 and 3.33 mg/kg respectively. Several reclaimed areas contain very low levels of phosphorus (1.90 mg/kg) and potassium (62.0 mg/kg).

Table 5. Summary statistics of average chemical properties measured for coversoils on the fourteen reclaimed sites.

Coversoil Chemical Properties	*Mean*	*Max.*	*Min.*	*Std. Dev.*
pH (-log [H^+])	7.65	8.40	6.40	0.56
Exchangeable Acidity (meq/100g)	0.03	0.08	0.00	0.02
Cation Exchange Capacity (meq/100g)	14.36	19.90	9.00	3.31
Electrical Conductivity (mmhos/cm)	0.20	0.32	0.08	0.07
Total Kjeldahl Nitrogen (mg/kg)	295.71	570.00	40.00	164.19
LECO Total Nitrogen (mg/kg)	0.00	0.06	0.02	0.01
Nitrogen as NH_4^+ (mg/kg)	2.19	5.10	0.70	0.99
Nitrogen as NO_3^- (mg/kg)	1.15	4.40	0.10	1.28
Plant Available Nitrogen (mg/kg)	3.33	9.50	0.70	1.97
Olsen's Phosphorus (mg/kg)	11.10	25.90	1.90	6.04
Extractable Potassium (mg/kg)	159.00	442.00	62.00	83.73
LECO Total Organic Carbon %	0.49	0.96	0.17	0.21
Organic Matter %	0.36	1.06	0.08	0.29
Carbon to Nitrogen Ratio (C:N)	13.00	17.45	9.44	1.98

According to *Munshower, 1994*, soil organic matter on reclaimed lands should be considered very low at concentrations less than 2.0%. This value is relatively high based upon the classification for a fertile Mollisol soil, where organic matter percentages must be at least 1% (*U.S. Dept. of Agriculture, 1999*). The maximum organic matter percentage on the Butte reclaimed areas sampled was 1.06%, while the average organic concentration measured only 0.36%. Nitrogen mineralization generally occurs through microbial activities with carbon to nitrogen (C:N) ratios less than 20:1. On the Butte reclaimed areas sampled, the maximum C:N ratio was detected at 17:1 with an average C:N ratio equal to 13:1.

Total trace element criteria for Cu (<250 mg/kg), Pb (<100 mg/kg), Cd (<4 mg/kg), Zn (<250 mg/kg), and As (<97 mg/kg) (*AERL, 1999*) were exceeded on only several reclaimed areas.

Table 6. Summary statistics of average DTPA and total trace element concentrations measured in coversoils on the fourteen reclaimed sites.

DTPA & Total Trace Element Concentrations	*Mean*	*Max.*	*Min.*	*Std. Dev.*
DTPA Copper (mg/kg)	6.67	31.12	0.51	6.91
DTPA Iron (mg/kg)	1.66	9.13	0.04	2.19
DTPA Lead (mg/kg)	2.06	8.10	0.10	2.20
DTPA Cadmium (mg/kg)	0.10	0.36	0.03	0.08
DTPA Aluminum (mg/kg)	0.01	0.14	0.04	0.07
DTPA Chromium (mg/kg)	0.03	0.03	0.03	0.00
DTPA Arsenic (mg/kg)	0.12	0.23	0.07	0.04
DTPA Manganese (mg/kg)	2.66	8.02	0.20	1.88
Total Copper (mg/kg)	191.36	631.00	27.00	161.87
Total Iron (mg/kg)	4.00	5.48	2.82	0.62
Total Lead (mg/kg)	103.96	692.00	15.00	171.92
Total Cadmium (mg/kg)	1.97	5.60	0.90	1.14
Total Zinc (mg/kg)	313.82	1588.00	87.00	384.76
Total Arsenic (mg/kg)	23.64	50.00	9.00	12.16
Total Manganese (mg/kg)	1484.64	2536.00	605.00	541.28

Criteria for DTPA extractable elements and total Fe and Mn have not been established for Butte revegetation specifications. Trace elements effects for Butte reclaimed area plant growth are discussed in later sections.

Surface vs. Subsurface Soil Properties

Coversoil samples were collected on the fourteen reclaimed areas at two different depth increments. Surface coversoils were sampled at 0-10 cm and subsurface coversoils were sampled at 10-40 cm. On shallow coversoils, subsurface coversoil samples were collected between 10 cm and the lime rock barrier, excluding the collection of lime rock particles. Surface and subsurface data sets were compared to determine if differences throughout the coversoil profile could be affecting plant growth. The upward migration of low pH water and trace elements from underlying mine waste through the lime rock barrier could be a major concern for plant growth. No significant differences ($p<0.05$) in trace element concentrations or pH were detected between the surface and subsurface coversoil samples when compared with a one-way ANOVA test. On reclaimed sites with coversoils deeper than 40 cm, subsurface coversoil samples were not collected directly above the lime rock layer where the upward migration of trace elements would contaminate soils. However, soil sampling pits were excavated to the lime rock layer on all sites and no visual evidence of upward migration of trace elements or low pH water was detected.

Significant differences were only detected between surface and subsurface coversoil depth samples when comparing plant available nutrient concentrations of nitrogen, phosphorus, and potassium and soil organic matter. Plant available nutrient concentrations are greater in surface coversoils likely due to reclamation maintenance activities involving occasional applications of granular fertilizer across the ground surface.

Simple Linear Regression Results

Coversoil data collected May 1999 (Appendix C) have been correlated with total plant canopy cover data collected August 2000 (Appendix B) to determine if any significant trends exist in these data that explain declining vegetative conditions on Butte reclaimed areas. Total and desirable plant canopy cover data displayed in Table 3 form the basis for linear correlations between independent variables including coversoil data, reclaimed site characteristics, and weather effects. Total plant canopy cover data, often considered as the primary indicator of reclamation success by the EPA and Butte-Silver Bow County, served as the dependent variable in linear correlations. Table 7 displays a variety of independent variables that were linearly correlated with total plant canopy cover, the regression equation, r^2 value, and p-value.

An ANOVA performed in *SPlus 2000*, calculated the regression fit using sums of squares of decomposition. The decomposition indicated how much each factor contributed to the total variance in the model. The F-statistic and corresponding p-value for each term tested whether that term contributed significantly to the model.

Coversoil depth, potassium concentration, plant available water holding capacity, precipitation received following fall seeding (October to July), fine earth index, and texture (clay index and clay + silt index) were all found to be significant when correlated with total plant canopy cover for the fourteen Butte reclaimed areas assessed.

Table 7. Simple linear regression results of total plant canopy cover verses various soil and precipitation variables. Total plant canopy cover is the dependent variable (y) in all equations.

Independent Variable	*Equation*	r^2	*p-value*
Coversoil Depth (cm) *	y = 0.63x + 38.82	0.59	0.0014
Nitrogen (N) (mg/kg)	y = 3.83x + 40.60	0.22	0.0944
Potassium K (mg/kg) *	y = 0.09x + 40.43	0.32	0.0365
Potassium K Index	y = 26.35x + 58.05	0.00	0.8961
Phosphorus P (mg/kg)	y = 0.08x + 57.43	0.00	0.9170
Phosphorus P Index	y = 0.01x + 57.36	0.00	0.8382
Coarse Fragments (%)	y = - 0.33x + 68.66	0.08	0.3283
Fine Earth Index *	y = 0.74x + 34.27	0.60	0.0011
Clay (%)	y= 0.96x + 46.24	0.04	0.4723
Clay Index *	y= 10.56x + 38.72	0.54	0.0027
Clay (%) + Silt (%)	y = 0.05x + 57.07	0.00	0.9423
Clay + Silt Index *	y = 4.40x + 38.31	0.50	0.0048
Clay + Coarse Fragment Index *	y = 11.84x + 42.97	0.47	0.0065
Clay + Silt + Coarse Fragment Index *	y = 5.09x + 42.36	0.46	0.0077
H_2O at Field Capacity (%)	y = 1.03x + 49.62	0.05	0.4503
Plant Available Water Holding Capacity (Vol. %) *	y = 24.36x + 43.02	0.46	0.0076
Precipitation (October – July) *	y = 8.99x - 25.20	0.30	0.0445
pH	y = - 13.26x + 158.54	0.28	0.0500
Cation Exchange Capacity ($mmol_c/g$)	y = - 0.029x + 59.11	0.00	0.9800
C:N Ratio	y = 1.04x + 51.05	0.04	0.5170

* Significant linear regression equation.

Index values were calculated by multiplying the independent variable by the average coversoil depth measured on each reclaimed area. The index values represent a depth weighted measure of a specific independent variable for the coversoil profile as a whole (e.g. clay index is a depth weighted measure of clay content for the profile as a whole). It is important to note that the index values discussed in the following sections are significant, yet are also very dependent upon coversoil depth. Trace element regression equations were excluded from Table 7 because no significant trends were detected when correlating total plant canopy cover with both total and DTPA extractable trace element concentrations.

Multiple Linear Regression Results

A number of independent variables were studied with multiple linear regression analysis to determine if combined factors have more importance than one single variable. Table 8 displays several of the multiple linear regression equations performed in this study. Major differences between each of the significant multiple regression equations are difficult to discern due to the similarities of independent variables involved.

Table 8. Simple multiple linear regression results of total plant canopy cover verses various soil and precipitation variables are displayed. Total plant canopy cover is the dependent variable (y) in all equations.

Multiple Linear Regression Equation	r^2	*p-value*
y = 1.40 Depth + 1.86 N – 0.12 CF + 30.71 *	0.65	0.0121
y = 1.47 Depth + 1.97 N + 1.17 % Clay + 10.47 *	0.70	0.0053
y = 1.19 Depth + 3.44 Precipitation + 1.80 N + 1.52 %Clay – 20.87 *	0.72	0.0140
y = 0.91 %Clay + 0.49 %Silt + 4.45 N – 0.03 %CF + 18.79	0.28	0.5103
y = 0.72 %Clay + 3.67 N – 0.10 %CF + 35.21	0.27	0.3585
y = 0.90 N – 0.44 P + 0.09 K + 43.27	0.35	0.2087
y = 3.07 N – 0.23 P – 0.02 K + 24.57 PAWHC + 35.77	0.57	0.0823

* Significant multiple linear regression equation.

Coversoil depth was included in all significant multiple linear regression equations and was consistently the significant variable involved according to ANOVA tests. The multiple regression equations further illustrate the influence of coversoil depth on total plant canopy cover. Significant relationships among total plant canopy cover and important independent variables are detailed in the sections below.

Coversoil Depth

Coversoil depth was the most important variable driving reclamation success in the reclaimed sites studied. Significant correlations were consistently found when coversoil depth was compared to plant canopy cover through linear regression and one-way ANOVA mean comparison tests. Table 9 displays the average coversoil depth and the individual depth measurements collected from the three soil pits excavated on each reclaimed area.

Table 9. Average coversoil depth and individual depths measured in soil pits excavated on the assessed reclaimed areas.

Sample Location	Pit #1 Depth (cm)	Pit#2 Depth (cm)	Pit#3 Depth (cm)	Average Depth (cm)
Late Acquisition *	71.12	45.72	66.04	60.96
Lexington Mill *	55.88	60.96	71.12	62.65
National	22.86	25.40	25.40	24.55
Original *	12.70	33.02	25.40	23.71
Otisco	20.32	12.70	17.78	16.93
Poulin	20.32	15.24	12.70	16.09
Star West Dump	27.94	43.18	38.10	36.41
Steward Mine Yard *	45.72	76.20	60.96	60.96
Tension Dump	45.72	45.72	45.72	45.72
Timber Butte Mill *	71.12	30.48	71.12	57.57
Travona *	40.64	50.80	45.72	45.72
Walkerville Ballfield *	45.72	60.96	60.96	55.88
Washoe Sampling Works	35.56	50.80	38.10	41.49

* Reclaimed area with successful uniform total live plant canopy cover >60%.

With the exception of the Original and Travona, reclaimed areas with at least 56 cm (22 in) coversoil contain a higher percentage of total canopy cover than those with less coversoil. Average coversoil depths measured on the fourteen reclaimed areas varied greatly from 12.7 – 71.1 cm (5 - 28 in). Average coversoil depths do not form an evenly distributed data set as shown in the histogram (Figure 6).

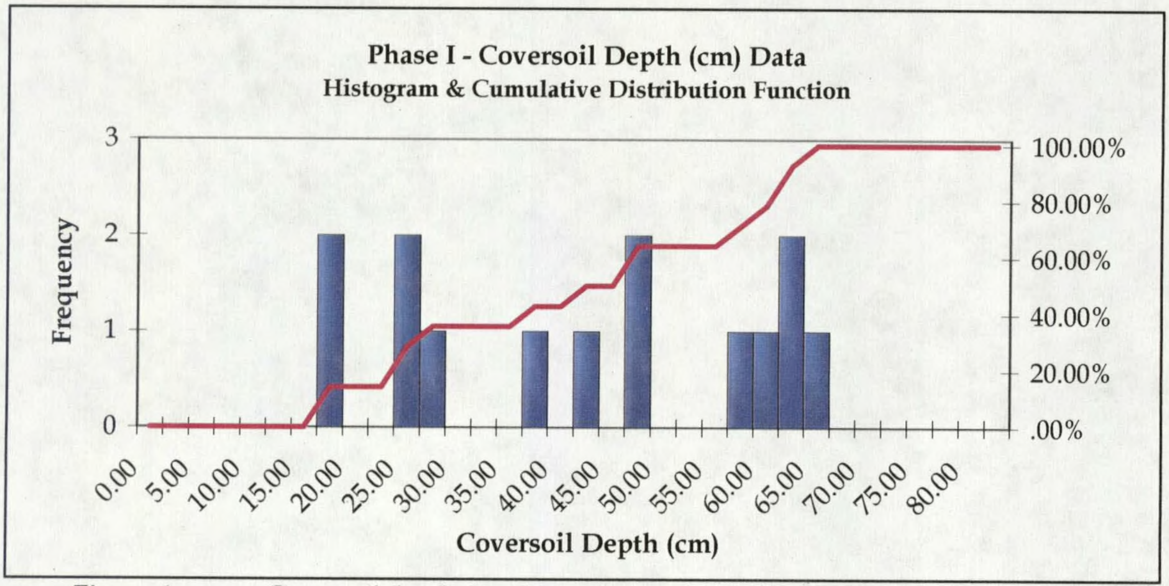


Figure 6. Coversoil depth data histogram and cumulative distribution function.

A break in the distribution of coversoil depths exists between 52.5 cm and 57.5 cm. Based on the break, the one-way ANOVA mean comparison test indicated that reclaimed sites with greater than 57.5 cm (22.6 in) of coversoil contained statistically higher total and desirable plant canopy cover values than reclaimed sits with shallower coversoil depths. The mean total plant canopy cover of 72.36% was measured on sites with greater than 57.5 cm of coversoil, whereas the mean canopy cover was 51.08% on sites with less than 57.5 cm.

Simple linear regression analysis of total canopy cover verses coversoil depth exhibited one of the strongest linear trends identified in the Phase I assessment (Figure 7). The regression equation (total plant canopy cover = 0.63 x coversoil depth + 32.82) yielded an r^2 value of 0.59. An ANOVA significance test performed in *SPlus 2000* determined the regression r^2 value to be significant ($p = 0.0014$). The regression equation for this data set predicts that total canopy cover may increase by 0.30 to 0.96% with each additional centimeter of coversoil.

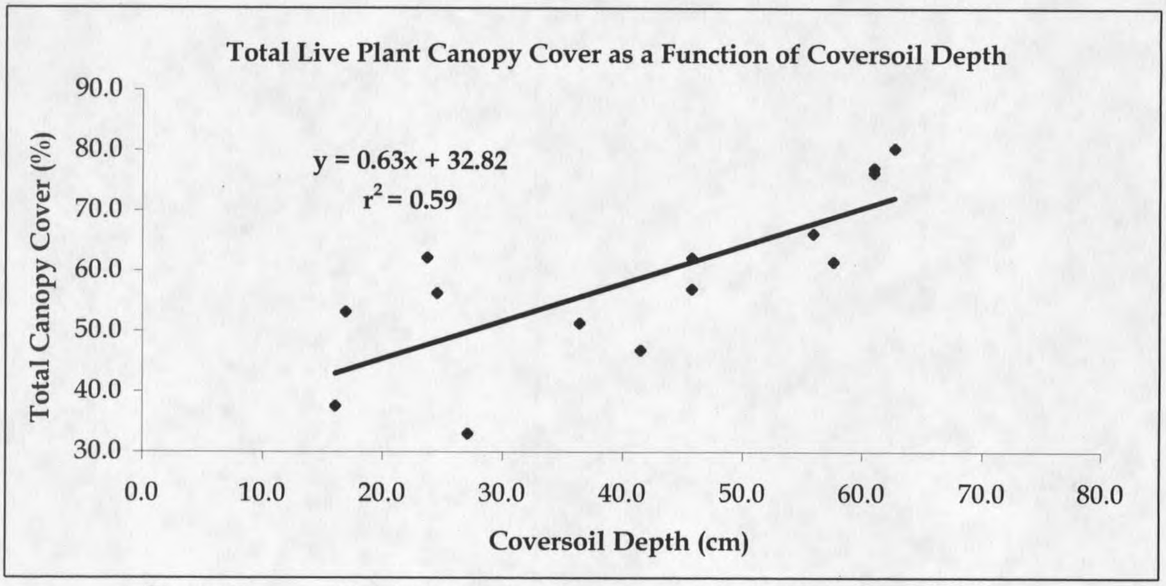


Figure 7. Total plant canopy cover correlated with coversoil depth.