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DEVELOPING TREES TOLERANT TO DEGRADED MINE SOILS IN AN UNDERGROUND GREENHOUSE

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DEVELOPING TREES TOLERANT TO DEGRADED MINE SOILS IN AN UNDERGROUND GREENHOUSE

by
Cosmas Opoku-Ware

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

Master of Science in Mining Engineering

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Abstract

This project explored the potential for developing trees tolerable to degraded un-reclaimed mine site soils and tailings as a solution to re-establishing long-term tree growth on those sites. The project incorporates growing tree seedlings in an underground greenhouse grown from seeds planted in the degraded mine soils in which they will eventually be planted. The outcome of the project is expected to lead to a successful solution for re-establishing tree growth in soils and tailings containing high metal concentrations with minimal post-planting human intervention at a relatively low cost.

The research is being conducted in an underground greenhouse located 100 feet below the surface in the Orphan Boy Mine Underground Mine Education Center (UMEC) located on Montana Tech's campus in Butte, Montana. The underground location is unique since it maintains a constant temperature year-round and insulates the young seedlings from inclement weather. Cost effectiveness being a goal of this project, the underground greenhouse is important since it will not require supplemental heat to be operable, minimizing cost of planting trees.

Trees native to Butte are being developed from seeds and planted in the underground greenhouse. Preliminary results show high survival rates of the planted seedlings in the soils and tailings. Continuous treating promises more seedling survival and subsequent tree growth which would help revegetate sites degraded by mine site soils and tailings.

Keywords: Underground greenhouse, Mine tailings, Native trees, Seed germination

Dedication

I dedicate this work to the memory of my father, James Nana Opoku-Ware. The foundation he built in my life has kept me strong and unwavering till this day. May his soul continue to rest in the bosom of God.

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Utmost thanks go to God Almighty for His guidance and protection throughout my graduate school journey at Montana Tech and for the successful completion of this thesis.

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1. Introduction

With the intent of improving Butte Area One natural resources, this research project was proposed to help restore tree growth within the Operable Unit Boundary. The Butte Priority Soils Operable Unit (BPSOU) is part of the Silver Bow Creek/Butte Area National Priorities List Superfund Site in Butte, Montana with multiple historic mining sites situated entirely within the urban setting (Blicker, et al. 2003). There is a dispersion of high amounts of mine wastes and mill tailings, accumulated from over 100 years of gold, silver, and copper mining throughout the area. These can pose health risks to human and environmental receptors.

Figure 1 shows a map of the Silver Bow Creek/Butte Area Super Fund Site (BASFS) and its Operable Units, giving more context to the environment that was impacted by historic mining and smelting. Stabilization of tailings is necessary because it prevents runoff of toxic materials into streams, reduces the volume of water seepage through acidic and heavy metal contaminated material, and controls fugitive dust (Watkin and Watkin, 1982). Water quality and stream flow will be improved in Silver Bow Creek if this project will be successful.

Trees native to Butte, Montana have been grown in an underground greenhouse located in the Underground Mine Education Center (UMEC) and will be planted in five areas located within the BASFS designated for tree planting by the Silver Bow County. Planting trees in the BASFS is expected to help restore vegetative ground cover within the watershed contributing to stream flow in Silver Bow Creek and prevent soils and tailings from eroding and being deposited in the stream where they could degrade water quality and alter stream flow.

Figure 1: The Butte/Silver Bow Creek Superfund Site and separable Operable Units, showing the Priority Soils Operable Unit (Ringsak, 2012)

1.1. Background

Currently, the research project is exploring the potential of growing tree seedlings to provide a resource for Butte that could produce thousands of tree seedlings each year adapted to the climate and soil conditions that exist in the BASFS where they eventually will grow. It is anticipated that the trees grown in the project will have the capability for long-term survival and growth because they will be germinated and grown into seedlings in soils and tailings collected from disturbed areas (soils and tailings) in the BASFS. Soils and tailings from the BASFS have been sampled and evaluated to determine if they lack nutrients or contain substances toxic to the long-term growth and survival of the trees. Potential amendments such as sewage sludge and lime will be evaluated as possible amendments to the soils and tailings to enhance the long-term

growth and survival of the planted trees. Applying sewage sludge, at a minimum, will add organic material to the growing media which will help retain soil moisture and may also provide some pH adjustment to acidic conditions that have been identified in the soils and tailings. These amendments should facilitate long-term tree growth and survival.

The techniques adopted for this project focus on promoting tree growth by following a natural revegetation approach with minimal human intervention and maintenance. This project is designed to be a synergistic resource working with other reclamation projects in the Butte area.

The underground greenhouse is a year-round facility that does not require supplemental heat thereby operating at a lower utility cost than a typical surface greenhouse. It is also insulated from inclement weather maintaining a constant temperature and humidity, which makes it unique. The relatively lower cost associated with operating the underground greenhouse will result in lower cost tree seedlings.

2. Problem Statement

Soils and tailings in the BASFS lack adequate vegetation cover to prevent them from eroding. Eroded sediments are being transported via surface runoff to Silver Bow Creek where they degrade water quality and affect stream flow patterns. Establishment and maintenance of a vegetative cover on capped tailings or directly in tailing materials can lead to an effective vegetative stabilization (Nemgar, 1987). This project seeks to develop a reclamation program to prevent erosion of soils and tailings by facilitating planting of trees in degraded areas within the BASFS with minimum long-term human intervention.

Trees are being grown from seeds in the degraded soils and tailings in which they will eventually be planted. It is believed that the tree seedlings grown underground will be able to better withstand the harsh growing conditions in Butte area than those grown in other greenhouses. Trees and shrubs once grew in the BASFS in the past before it was settled, without human intervention. Trees should be able to grow and survive there again without human intervention.

An underground greenhouse has been developed approximately 100 feet below the surface in the UMEC on the Montana Tech campus for this purpose. Tree seedlings native to the Butte, Montana area are being grown from seeds in the greenhouse and hardened in a sheltered area to be planted in the BASFS. The underground greenhouse is expected to accommodate up to 4,000 seedlings a year. Tree seedlings grown in the underground greenhouse will be made available to any reclamation project desiring trees in the Butte area.

2.1. Project Goals

This project is expected to become a long-term research resource available to other projects focused on restoring the Butte landscape with native trees long after the project is completed. The long-term goal, to restore and maintain water quality in Silver Bow Creek by growing trees, will be accomplished by pursuing the following objectives:

- Establish a functional underground greenhouse in the Montana Tech UMEC.
- Sample and analyze soils and tailings from prospective planting sites in the BASFS to determine if there are any needed amenities.
- Acquire seeds of native tree species from seed suppliers and the Montana Tech Native Plant Restoration Project, pretreating and priming them for germination.
- Plant the germinated seeds in BASFS soils and tailings and nurse the resulting seedlings to maturity.
- Harden the seedlings in a semi-sheltered environment prior to planting.
- Plant seedlings on the selected sites.

3. Literature Review

The literature review focused on topics relating to mine tailings and their impacts, methods of stabilization and the underground greenhouse concept. Research in this section also covered mineral wastes, species selection and tree growth and application of amendments to enhance tree growth.

3.1. Mineral Wastes

Mineral wastes (tailings) are characteristics of landscapes where the extraction of mineral resources have been conducted. According to Nemgar (1987), mineral wastes are often found in areas with harsh climatic conditions such as short growing seasons, prolonged low temperatures, drought and strong winds.

Metalliferous mining produces waste of two distinct physical forms. Very coarse waste rock (diameters usually 2–20 cm) consists mainly of demineralized overburden rock, excavated to uncover the ore-body, and rock from areas within the ore-body which contains metals at concentrations below the cut-off grade. Tailings, on the other hand, are fine-grained (< 2 mm) deposits from final stage separations (Tordoff et al. 2000). According to Dean and Shirts (1975), approximately 40 percent of mineral wastes consist of fine sized materials deposited as tailings.

Mine tailings generally fall in the pH range of 1.5 to 8 with problems occurring when the pH drops below 5.5 (Williamson et al., 1980). High concentrations of hydrogen ions cause inactivation of most enzyme systems, restricting respiration and root uptake of minerals and water, which is a direct effect of acidity on plant growth.

Not disregarding the enormous economic prosperity associated with heavy metal mining, there are historically large areas of industrial abandonment once mining activities ceased. The abandonment may leave a pile of tailings, which contains waste products of both mining and ore

processing operations. Such materials form the basis of a major source of heavy metal pollution in the environment owing to dust blown from and the leaching of the products of mineral weathering into nearby watercourses.

The Citizen Technical Environmental Committee of Butte, Montana reports that, the intensive historic mining and smelting activities in Butte and Anaconda is a perfect example of how mining operations can cause damages to the environment (Ringsak, 2012). These activities have had serious environmental consequences for the entire Upper Clark Fork Basin, consequences that have persisted for over 100 years and will continue to require community attention and management for the foreseeable future. Figure 2 shows the deposition of mine tailings along the Silver Bow Creek as a result of mining operations.

Figure 2: Mine Tailings along the Silver Bow Creek floodplain (Ringsak, 2012)

This pollution may have serious detrimental effects on crops and public health (Smith and Bradshaw, 1972). Firth et al., (1981) gives an example of the despoliation of a large area non-productive agricultural land owing to toxicity to arable crops as a result of a washout of tailings from the Parc lead/zinc mine in North Wales. These mining activities have negative impacts on the environment due to the deposition of high volumes of wastes on the soil. Dudka and Adriano (1997) further confirmed that the negative impacts of past mining activities on the surroundings is mainly a result of the presence of high volumes of tailings. There are now federal and state laws such as the Surface Mining Control and Reclamation Act of 1977 (SMCRA) that regulate the stabilization of tailing sites due to the impacts they have on the environment.

3.2. Method of Stabilization

3.2.1. Revegetation

Coppin et al. (2000) defines revegetation as “the process of vegetation establishment and aftercare undertaken as part of reclamation, rehabilitation or restoration”. The main purpose of revegetation is to stabilize mining spoils with a self-propagating plant community. This in turn, helps to reduce wind, water and groundwater pollution and increases aesthetic appearance and provides for land use such as grazing.

Sheoran et al. (2010) asserts that, reclamation strategies must address soil fertility and structure, microbe populations, top soil management and nutrient cycle so as to return the land as closely as possible to its original condition and be able to continue as a self-sustaining ecosystem. Reclamation and revegetation of abandoned mined lands are often limited by physical and chemical properties existing in the soil, including (but not limited to) low pH, high metal levels, low nutrient levels and poor or no soil structure (Said, 2009).

Barth (1986) and Donovan et al. (1976) suggest that steps in successful revegetation encompasses the evaluation and modification of the growing medium, selecting proper species, preparing and planting the seedbed and monitoring. Modifications of growing media are conducted to counteract limiting factors (Nemgar, 1987).

Mine tailings with varying levels of metal concentrations can have high impacts on vegetation and the environment and are characterized by low fertility. Erosion is another problem of unreclaimed mine tailings where original soils are removed and deposited off-site, often resulting in negative environmental problems to those areas.

According to Hector et al. (2006), removal of mine tailings is often impractical due to their large volumes of material. Thus, a need exists to develop in-situ low cost technologies to effect surface stabilization. The use of vegetation can be an attractive option, since there are some native plant species that can colonize parts of these polluted sites unaided.

Tordoff et al. (2000) suggests that while there are a range of reclamation techniques available for metalliferous substrates, only through the use of vegetation to stabilize mine wastes can complete long-term rehabilitation be achieved. They further add that successful revegetation can be a permanent and visually attractive solution and, at the same time, be relatively inexpensive. It is now widely accepted that stabilization by vegetation is far more desirable than any other methods. McDonald and Shirts (1978) confirm that vegetative stabilization is the preferred method because it is more permanent, has better aesthetics and allows a wider range of future land uses.

Vegetation, in most instances, is the most effective and least costly way to stabilize tailings against wind and water erosion and to reduce water seepage through the tailings (Barth, 1986). However, Nemgar (1987), argues that, the vegetation approach to stabilization of tailings

sites is the more difficult to achieve due to the physical and chemical characteristics of the tailings.

Revegetation constitutes the most widely accepted and useful way to reduce erosion and protect soils against degradation during reclamation (Sheoran et al., 2010). Adequate vegetative cover can effectively prevent surface erosion, prevent wind-blown contaminated particulates and reverse degraded soil back to its original state through development of a firm root system and further results in increased soil organic matter, enhanced mineral nutrient availability and moderate pH.

3.3. Species Selection

Barth (1986) and Watson et al. (1980) define species selection as “the process involving the matching of plants with the phytotoxic nature of the soil; i.e., acid tolerance, metal tolerance, salt tolerance, etc. Other considerations include drought tolerance, rooting depth, palatability and flood tolerance”.

According to Mensah (2015), species selection will depend on local soil and climatic conditions but should aim to provide a uniform rather than clumpy pattern of vegetation to avoid concentrations of runoffs and localized erosion. However, the ideal condition is difficult to achieve where the soils have low water retention capacity, are toxic, or where cold, drought or exposure inhibits plant growth. Special consideration of the weather pattern is also important in selecting species for revegetation purposes.

Donovan et al. (1976) suggests that the success of a reclamation project is highly dependent on the choice of plants used. The plants used must match the habitat because; the use of native species has a greater possibility of eliminating climate concerns. Research conducted by Williamson, et al. (1980) points out that native plants growing near waste sites have adapted

over generations to withstand the rigors of their environment. Bradshaw et al. (1978) also reveals that plants collected from waste sites have been shown to be tolerant to the metals present in the growing medium as a result of evolution through natural selection.

Several site specific factors inhibit the establishment of vegetation on tailings and other mine wastes (Barth, 1986b). Some natural vegetation however, thrive on mine wastes despite site specific limitations.

Factors to be considered with regard to the characteristics of the mineral wastes when selecting plant species include metal toxicity, acidity and salinity (Barth, 1986b; Williamson, et al., 1980). Metal tolerant plants can be effective for acid and heavy metal bearing soils (Sheoran et al., 2010).

Species selection should also reflect the land use objectives of the reclamation program whether it is erosion control, wildlife habitat, aesthetics or economic production (Donovan, et al., 1976). If revegetation efforts are to succeed, plants species capable of tolerating the adverse conditions of the waste sites must be selected (Donovan, et al., 1976; Williamson, et al., 1980).

3.4. Tree Growth

3.4.1. Seed Germination

Germination begins with the uptake of water by dry seeds and ends with the elongation of the embryonic axis. Seed germination is a complex and dynamic stage of plant ontogeny, with a number of interactive metabolic processes undergoing changes from a storage phase to a mobilization phase (Bewley and Black, 1994). Favorable external conditions are needed to aid in germination, if not, the seed will remain in a quiescent state; a state of persistent viability (Krugman et. al., (1974). According to Barton (1965), the length of time a seed can remain in a

quiescent state before it completely loses its ability to germinate is highly variable from a few weeks to many years.

The penetration of the structures surrounding the embryo by the radicle is the visible sign that signifies the completion of the germination process (Bewley, 1997). According to Bradford (1995), seed germination passes through three distinct phases: Phase I, the imbibition process, is the stage in which water is taken up by the seeds but little metabolic activity takes place; Phase II, a lag phase in which considerable metabolic activity takes place but there is little water uptake by the seeds; and, Phase III, characterized by an increase in water content coinciding with radicle growth and emergence. The length of Phase III is important because germination is considered complete when embryo growth is initiated. This triphasic cycle is illustrated in figure 3. The time taken for the events in Figure 3 to occur varies between species and is influenced by germination conditions.

Figure 3: Time course of physical and metabolic events occurring during germination (Phase I and II) and early seedling growth (Phase III). (Bewley, 1997; Nonogaki, Bassel & Bewley, 2010)

3.4.1.1. Environmental Requirements

Germination of a viable seed is dependent on favorable environmental conditions. A completely nondormant seed has the capacity to germinate over the widest range of normal physical environmental factors possible for the genotype (Baskin and Baskin, 1998, 2004). Temperature is the major environmental factor that causes changes in seed dormancy states, but other factors such as moisture, light, and adequate gas exchange may be very important (Baskin and Baskin, 1987a). These environmental factors are interdependent on each other and their relative influence on germination will vary with the age and genetic composition of the seed and how it is handled (Krugman et al., 1974).

3.4.1.1.1. Adequate Moisture

The level of seed hydration plays an important role in seed germination. Viable seeds must absorb enough water before they are able to resume the digestive, translocatory and assimilatory processes necessary for embryo growth viability. Adequate moisture also aids in oxygen and carbon dioxide exchange among seed tissues (Krugman et al. (1974).

According to Goo (1956), seeds of many species absorb water more rapidly at higher temperatures and the absorption rate is dependent upon degree of seed coat permeability. Soaking tree seeds is encouraged only for a short period of time and will not decrease germination. However, care must be taken when soaking seeds of upland species. Toumey and Durland (1923) found that soaking seeds such as western red-cedar (*Thuja plicata*) and red pine (*Pinus resinosa*) for 10 days reduced germination and soaking for 30 days killed the seeds. Hill (1985) suggested that frequent light watering of seeds is better than heavy soaking every day.

3.4.1.1.2. Light

Light stimulates the germination of many species of seeds. The effects of light on seeds is dependent on the internal condition of the seeds and external factors such as temperature under which they are germinating (Krugman et al., 1974). Germination of some species is better under continuous light. Both Douglas fir (*Pseudotsuga menziesii*) (Jones 1961) and Jack pine (*Pinus banksiana*) (Ackerman and Farrar 1965) germinate rapidly under continuous light at temperatures of 21° or 27°C. Jones (1961) points out that for some species alternate periods of light and darkness can substitute for continuous light. For example, Douglas fir (*Pseudotsuga menziesii*) seeds will germinate as well within 16 hours of light in a 24-hour cycle as in continuous light. Botha et al. (1982b) suggests that light can prevent germination of negatively photoblastic (light inhibited) seeds. For example, the germination of watermelon (*Citrillus lanatus*) seeds was inhibited by white and far-red light but was stimulated by red light. According to Gorski and Gorska (1979), natural sunlight at high irradiances inhibit the germination of some seeds but low irradiances promoted germination.

3.4.1.1.3. Gas Exchange

Research conducted by Mayer and Poljakoff-Mayber (1963) found that the respiration which fuels metabolic processes during germination requires oxygen and produces carbon dioxide. Thus, composition of the ambient atmosphere can have a direct influence on seed germination by its effects on gas exchange.

Oxygen, carbon dioxide and ethylene occur in the gaseous environment of soils, and each may influence seed dormancy and/or germination (Baskin & Baskin, 1998). According to Egley, (1986), the level of carbon dioxide in soils depends on depth, temperature, moisture levels, porosity, and amount of biotic activity and rates of gas exchange with the air. Most seeds will not

germinate when the germination medium is too wet, when the seeds are planted too deep, or when other conditions limit the supply of oxygen.

The rate of oxygen absorption during seed germination is highly variable among species (Hosner, 1957). Seed development will cease under conditions of insufficient oxygen since oxygen is essential for normal seed development (Krugman et. al., (1974). Regular oxygen uptake follows a pattern similar to that of moisture.

3.4.1.1.4. Temperature

Different tree and shrub seeds can germinate over a wide and different range of temperatures. A few species have an optimum germination temperature which may vary depending on the conditioning they have received (Krugman et. al., (1974). Germination of most species, however, is not directly temperature dependent. The optimum germination temperature may vary between individual trees in a stand as well as between populations of a given species (Olson et al. 1959). Seeds of most bedding plants germinate best when kept between 24° and 27° C. From the time seeds are planted until the plants develop their first true leaves, temperatures should be kept relatively constant throughout the day and night (Hill, 1985).

Very high and very low temperatures prevent germination of most tree seed. Pitch pine (*Pinus rigida*) will germinate at temperatures up to 57° C, but this ability is not common (USDA Forest Service 1948). Temperature regimes prevailing during germination under nursery and field conditions are characterized by wide fluctuations from below freezing at night to perhaps 21° to 27°C during the daytime in the surface soil containing the seeds. Seed of some 17 genera and 64 species of woody plants have been classified as being more responsive to alternating than to constant temperatures (Hatano and Asakawa 1964). AOSA (1965) revealed that temperature

alternating diurnally from 30° to 20°C are recommended for laboratory germination tests on about 100 species.

3.4.1.2. Stratification

The term stratification is commonly used to describe all forms of moist conditioning of seeds from the process of pretreating seeds to simulate natural conditions that a seed must go through before germination. Many seeds with physiological and/or physical dormancy require exposure to either high or low temperatures before being placed in conditions favorable for germination (Krugman et. al., (1974).

Krugman et al. (1974) further emphasized that the procedure mostly used in stratification is to place seeds in low temperatures (1° to 5° C.) and under moist conditions from one to six months. This low temperature conditioning causes gradual and progressive internal physiological changes whose effect is shown in both the number of seeds germinated and in the time it takes for a seed to germinate. Hill (1985) found that, stratification softens the seed coat so water can pass through it, permitting the seeds to develop into a tiny embryo.

Cold-wet stratification is regarded as the most important way to break dormancy in seeds of summer annuals and most temperate perennials (Baskin & Baskin 1988; Probert 1992). During exposure to low temperatures, the range of temperatures over which seeds will germinate as well as germination percentages increase (Baskin & Baskin 1980, 1988).

Cavieres et al. (2000) found that, for all seed populations, at each stratification period, final germination with stratification was significantly higher than germination without it. Bewley and Black (1982) found that, for many plant species, cold stratification increases germination. For many seeds, such as pines (*Pinus*), Douglas fir (*Pseudotsuga menziesii*) and Eastern Hemlock (*Tsuga canadensis*), germination occurs at a progressively wider range of temperatures

with increased duration of stratification (Hatano and Asakawa 1964). Stratification is also important because conditioning dormant seeds under moist conditions also permits the leaching of possible inhibitors from the seed coat or fruit parts adhering to the seed coat.

3.5. Amendments

The principal nutrients needed for plant growth are nitrogen (N), phosphorus (P) and potassium (K) (Nemgar, 1987). Tailings lack the necessary elements and nutrients to sustain plant growth and often contain constituents that impede plant growth; hence, modification is necessary to support vegetative cover (Barth, 1986b)

Acidic mine spoils such as the Silver Bow Creek watershed tailings can be neutralized with lime (Nemgar, 1987; Torrence, 1986). Nutrients can be supplied immediately with fertilizer or stored in a slow release form such as sewage or manure (Barth, 1986). Organic material such as straw, manure and sludge can form chelates with four metals and increase microbial activity, water retention, nutrient capacity, etc. (Barth, 1986; Donovan et al., 1976).

3.5.1. Lime

Research conducted by Johnson and Bradshaw (1977) found that acidic mine spoils are characterized by soluble metal toxicity, hydrogen ion toxicity and a lack of nutrients. Pyritic mine spoils are especially toxic because they release sulfuric acid during weathering.

Lime addition has been proven to raise the pH and subsequently tie up heavy metals, remove or neutralize H^+ ions and increase the availability of nutrients (Torrence, 1986; Nemgar, 1987; Buckman and Brady, 1969). However, Lexmond and Van Der Norm (1981) found that raising the pH can also lead to the increase in toxicity of copper and result in the reduction of root growth and nutritional uptake. Torrence (1986) points out that, acid intolerant species will

not grow on local mine spoils without the addition of lime. Therefore, lime must be added as an amendment for germination to take place on tailings.

According to Down (1974), slaked lime and quicklime are sometimes used in neutralization of mineral wastes but there is an enormous danger to plants if over applied than with limestone. Excessive liming raises the pH beyond the optimum required for plant growth and has the tendency of restricting uptake of nutrients by plants (Harwood, 1979). Due to the enormous variability between wastes, lime requirements to allow establishment of vegetation on tailings must be determined for each site (Down, 1974) and its application rate must account for both past and future pyrite oxidation to maintain neutralized soil pH levels over time (Sheoran et al. 2010).

3.5.2. Fertilizer

Insufficient application of fertilizer can result in failure of any revegetation program. Over fertilization can also be harmful causing stunted growth (Barth, 1986b). It is therefore necessary to apply fertilizer in required quantities to support revegetation. The exact composition of the fertilizer and the form and rate of application depend on the characteristics of the tailings and the species planted (Down, 1974; Barth, 1986b). Newly created mine soils, and many older ones, will require significant fertilizer applications for the establishment and maintenance of any plant community (Sheoran et al., 2010).

Maiti and Ghose (2005) reported that increase in pH and organic matter content is essential in achieving a sustainable reclamation of mining overburdens. Organic matter is the major source of nutrients such as N, and available P and K in unfertilized soils. Some of the metallic micronutrients essential for plant growth are iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) and are usually available in soils due to continuous weathering (Donahue et al.,

1990). Donovan et al. (1976) points out that, grasses invariably need N but do not necessarily respond to additions of P and K. They also found that locally available drought resistant, fast-growing trees able to grow in acidic nutrient deficient soils increased the concentration of available Fe in all reclaimed dumps higher than 4.5 mg kg⁻¹, Mn with average value of 13 mg kg⁻¹, 9 to 42 mg kg⁻¹ for Zn, and 0.32 to 1.22 mg kg⁻¹ for Cu. Organic amendments such as municipal sewage sludge, manure, sawdust, straw and peat have been used to increase pH and shown to be valuable in promoting revegetation of acidic mine wastes (Barth, 1986b; Down, 1974; Hill and Montague, 1976).

3.6. Greenhouse Strategy

Hanan (1998) describes a greenhouse as “a structure covering ground for growing crops that will return profit to the owner risking time and capital”.

3.6.1. Underground Greenhouse Concept

An underground greenhouse can be classified under the closed greenhouse concept since it maintains a relatively constant temperature and humidity. Vadiie and Martin (2012) reiterate that using the closed concept, the greenhouse becomes independent of the weather situation and could be used in predominately hot and arid regions. In principle, this suggests that an underground greenhouse can be used as a year round facility.

An experimental project undertaken by Hudson Bay Mining & Smelting (HBM&S) and Prairie Plant Systems Inc. of Saskatoon, Saskatchewan grew hundreds of red and yellow roses as well as juicy red tomatoes and Saskatoon berry bushes far beneath the ground in Flin Flon, Manitoba, Canada. The plants were grown in an underground hydroponic garden (old dynamite storage room carved into the rock) located 360 meters below ground surface in a mined out

portion of the Flin Flon Mine. The purpose of the experimental project was to determine the appropriate technology that could be used to produce fresh vegetables, fruit and flowers in any remote mining community in Canada or other parts of the world.

The 75 square meter garden is accessed using the mine's main hoist and a 1.5 kilometer tracked drift. It was illuminated by twenty 1,000-watt high pressure sodium and metal halide lamps switched on for 18 hours a day to keep the plants growing at a maximum rate. Temperatures recorded in the greenhouse ranged between 15° and 26° C depending on when the lights were on or off (Fraser, 1991). Figure 4 shows the underground greenhouse located at the 1,170-foot level in the Flin Flon Mine in Manitoba, Canada.

Figure 4: Flin Flon North Main Underground Greenhouse (Flin Flon Community Archives, 1991)

The first use of an underground mine for large scale production of plants for practical applications is believed to have happened at the Bunker Hill Mine in Kellogg, Idaho. The accidental planting of an orange seed by an unknown miner decades ago led to the conversion of a tunnel in the Bunker Hill Mine into an underground greenhouse for the production of pine trees

(“Old Mine Grows Pine Trees”, 1976). In 1972, Ed Pommerening, a forestry major at the University of Idaho, was hired by Bunker Hill Mine to lead a revegetation project at the mine that led to the successful full-scale production of pine trees in the mine (“Old Mine Grows Pine Trees”, 1976). The Bunker Hill Mine underground greenhouse is shown in Figure 5.

Figure 5: Bunker Hill Underground Greenhouse (Pommerening, 2016)

In the late 1970s, the Anaconda Copper Mining Company, developed an underground tree farm in the Kelly Mine in Butte, Montana to grow trees to plant during reclamation of lands disturbed by their mining activities (Kukay, 2017). The project successfully grew approximately 10,000 trees that were ready to be planted on the Anaconda reclamation sites. The trees were acclimated for growth and survival in the cold arid climate of Butte. Proof of this concept are trees growing on the Continental East mine dump area. After the company closed the Berkley pit in 1983 and shut off the mine pumps, the Kelly Mine flooded and destroyed the tree farm.

The concept of an underground greenhouse has been proven successful in other instances such as the Tygart limestone underground mushroom farm which began growing operations in June 1968 (Preston, 2015) and the Kimberly Diamond Mine's Big Hole mushroom mine which was started in 1998 in South Africa, by adopting the concept developed in Canada, Australia and the United States (Delaurentis, 2002).

3.6.1.1. Growth Rate and Temperature Requirements

It has been observed that plants grow and mature at an accelerated pace in the controlled underground climate and record massive successes as compared to above surface greenhouses (Cobb, 1997). Ramirez (1995) reported that although not everything grows well in the underground conditions, those that thrive do amazingly well, mature faster, become larger and yield larger crops. The underground greenhouse at the Bunker Hill Mine recorded an average of 40 percent higher survival growth rate of their pine trees grown underground than those grown outdoors in the traditional greenhouses. Pommerening found that the temperature of the Bunker Hill Underground Mine varied from 7° to 32° C, depending on the depth. The temperature at the greenhouse location, however, remained constant at 24° C year round. ("Old Mine Grows Pine Trees", 1976).

Copper mines have, by far, shown to be a perfect underground greenhouse environment due to the abundance of carbon dioxide in the air and the optimal growing conditions that can be created and controlled underground. Plants are protected from setbacks caused by insects, droughts, winds, etc., once the necessary growing conditions such as temperature, light, nutrients and water are properly regulated (Cobb, 1997). Noxious gases however, can affect crop production.

Temperature considerations have been a major factor in determining the use of an underground mine as a greenhouse. Preston (2015) reported that a group of Kentucky mushroom growers settled on using an abandoned underground limestone mine for mushroom production due to its cool and constant temperature that varied between 10° and 14° C with an ideal humidity of 85 percent.

According to Ramirez (1995), computers can play an essential role in managing an underground greenhouse. Temperature and humidity monitoring and the control of the on-off cycle of light can be done by computers. Temperature and humidity in a mine make a natural greenhouse for seedlings.

4. Research Approach and Field Methodology

4.1. Construction of Greenhouse

The UMEC is located on the Montana Tech campus approximately 100 feet below the surface. The center is a multidisciplinary facility used for practical mining, mining engineering classes and research. Figure 6 shows the underground greenhouse with the installed structures.

Figure 6: UMEC's Underground Greenhouse

4.1.1. Heading Construction

The greenhouse location was originally developed as a mining heading by students in Montana Tech's practical underground mining class. The heading was widened by students in the class to create more space when the decision was made to convert it into a greenhouse. The

roof and sides of the heading were reinforced with roof bolts and chain-link fencing to provide long-term stability.

The greenhouse contains a constructed growth platform to support tree growth and watering of the trees. To prevent potted trees from being knocked over and damaged by airblast waves and ground vibrations from blasting during the practical underground mining class, a four-foot by eight-foot lattice shelf with six-inch by six-inch openings was constructed to hold potted trees. A four-inch by four-inch steel mesh grid was placed above the lattice shelf to facilitate sprinkler watering.

4.1.2. Utilities

4.1.2.1. Power

Electricity was tapped from the already existing power grid in the UMEC and extended to the greenhouse to supply energy needed for the grow lights, sprinkler system and timers.

4.1.2.2. Water

Mine shaft water is used for irrigation in the underground greenhouse and has a pH of 7.5. A water distribution network already existed throughout the UMEC and was extended to the greenhouse. Potable water is hauled to the greenhouse to be used to water a section of seedlings to serve as a water control to evaluate the impact of using mine shaft water.

4.1.3. Sprinkler System

A misting sprinkler system has been installed to water the seedlings with a timer. Mine shaft water is stored in a 50-gallon watering trough which is pumped up and distributed to the sprinkler system. Currently, the seedlings watered with mine shaft water are watered by hand and eventually will be watered using the sprinkler system and a timer. Watering of the control

seedlings with potable water is done by hand. The quantity of water the seedlings receive by hand watering is the same as the quantity that will be applied using the misting sprinkler system.

4.1.4. Grow lights

Two eight-foot florescent grow lights have been installed above the lattice platform to provide the photo energy needed for the seedlings to grow. Timers are used to turn the grow lights on and off. The number of hours the grow lights stay on are in tune with the daylight time on the surface. Table I (adapted from <http://www.timebie.com/sun/buttemt.php>) shows the average daylight time for Butte, Montana for each month of the year. The timing of the grow lights have been set based on these figures.

Table I: Daily grow light duration for each month

Month	Approximate grow light duration
January	8 hours 45 minutes
February	9 hours 45 minutes
March	12 hours
April	13 hours 45 minutes
May	15 hours
June	15 hours
July	15 hours
August	14 hours 30 minutes
September	13 hours 45 minutes
October	11 hours
November	9 hours 45 minutes
December	8 hours 45 minutes

4.1.5. Greenhouse Management and Monitoring

The greenhouse is checked weekly to ensure it is functioning properly. The UMEC will eventually be connected to the Montana Tech computer network to monitor and control its

operation using computers located in the Mining Engineering Department. The UMEC currently has an operating Wi-Fi system that is connected to Montana Tech's computer network.

A Kestrel D3 fire humidity meter monitors temperature, relative humidity and station pressure in the greenhouse. Temperature in the underground greenhouse is relatively stable averaging of 7.5 °C (Table II) with relative humidity averaging 100%. These values are average values from a 4-month period data set. These parameters are considered essential to the survival of plants and will be monitored to determine their impact on seedling growth in the greenhouse.

Table II: Underground greenhouse temperature and relative humidity

	Temperature	Relative Humidity
Maximum	8.7 °C	100%
Minimum	6.8 °C	100%
Average	7.5 °C	100%

4.2. Growing Media

4.2.1. Degraded Soils

Soil and tailing samples were collected from five potential tree planting areas in the BASFS. Figure 7 shows the location of the sites. The samples were obtained unsized. Manual sieving of the samples through a No. 14 US mesh (1.4 mm) screen was conducted to remove coarse materials. The sieved material was crushed to a minus No. 14 size for use as a growing medium. Analyses of the samples were performed on the crushed fraction since finer material has more surface area per unit volume than the coarse material.

Figure 7: Aerial photo showing the 5 soil sampling locations

4.2.2. Laboratory Analysis

Analyses of the soil and tailings samples were conducted to determine potential needed amenities and the metallic contents of the samples. Heavy metals present for plant uptake are those present as soluble components in the soil solution or those easily solubilized by root exudates (Blaylock et al. 2000). The toxic effects of metals depend on the particular metal present. Research conducted by Johnson (1987) suggests that, if physical and chemical properties of mine waste materials in which vegetation is growing can be analyzed and related to plant growth, then it can be determined which soils properties plant populations can tolerate.

The laboratory analyses for the soils and tailings samples focused on determining pH, acid extractable metals, total major elements, mineralogy, and clay content. Slurry extract from Sample 2 showed high acidity and it may need amendments to support plant growth. Samples 1,

3, and 4 though acidic, should support plant growth, and would be more likely to do so with proper amendments. Sample 5 has the best pH to support plant growth.

Table III presents the acid extractable metals determined by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) analysis along with the percentage of solids present in the samples collected. All of the soil samples showed elevated levels of arsenic and lead. The major elements in the soils and tailings were determined using X-Ray Fluorescence (XRF) analysis on a finely ground specimen from the minus No. 14 US mesh material. XRF provides only total metals content and does not reflect bioavailability. At this point in time, analysis of bioavailability is beyond the scope of the project. Table IV presents the total metals that characterize the samples.

Table III: Acid extractable metals by ICP-OES - Dry weight (mg/kg)

Sample ID	1:1 pH	% Solids	Ag	As	Cd	Cu	Mn	Pb	Zn
MDL	--	--	1.6	0.14	0.05	0.65	0.45	0.10	0.73
Sample 1	5.82	94.7	44.3	24.6	18.9	144	4,625	2,928	3,242
Sample 2	1.97	95.8	73.7	183	4.08	75.0	607	816	312
Sample 3	4.88	97.0	74.2	175	8.75	156	7,905	4,780	2,385
Sample 4	6.06	96.4	12.5	115	19.3	71.6	12,401	2,346	5,494
Sample 5	8.43	93.3	<13	7.69	2.60	8.17	184	13.1	78.2

Table IV: Total metals by XRF (Wt. %)

Sample ID	Al	Ca	Fe	K	Mg	Mn	P	Si
Sample 1	6.47	1.40	4.94	3.18	1.01	0.62	0.06	22.7
Sample 2	8.30	0.49	2.85	5.68	0.62	0.11	0.06	21.9
Sample 3	7.07	0.44	1.58	4.73	0.19	1.07	0.04	29.0
Sample 4	7.86	1.62	3.24	4.07	0.80	1.36	0.05	23.4
Sample 5	9.74	1.78	1.61	3.09	0.91	0.02	0.04	32.0

X-Ray Diffraction (XRD) analysis was performed on the powdered samples (15 microns) to determine the major mineralogy present in the samples. The major constituents of the tailings were found to be quartz, feldspar and mica. Feldspars consisted of the K-Feldspars, microcline and orthoclase and the sodic feldspar, albite. Hornblende was a minor constituent in sample 1 at 1% and jarosite was minor in sample 2 at 2.5%. Sample 4 contained 5% pyrite and 2% calcite. The presence of these minerals should not contribute negatively to the potential for tree survival on any of the sample sites. Complete results from quantitative XRD are presented in Table V.

Table V: Mineralogy by XRD (Wt. %)

Mineral	Sample 1	Sample 2	Sample3	Sample 4	Sample 5
Quartz	19.3	42.3	45.0	46.7	11.5
Total Feldspar	55.7	23.8	47.3	21.9	88.4
Microcline	--	23.8	41.6	21.9	--
Orthoclase	22.9	--	--	--	22.1
Albite	32.8	--	5.7	--	66.3
Total Mica	23.9	31.3	7.7	24.1	--
Muscovite	23.9	25.3	7.7	13.8	--
Kaolinite	--	--	--	10.3	--
Lepidolite	--	2.1	--	--	--
Dickite	--	3.9	--	--	--
Hornblende	1.1	--	--	--	--
Jarosite	--	2.5	--	--	--
Pyrite	--	--	--	5.3	--
Calcite	--	--	--	2.0	--

4.3. Tree Species

Seeds being used in this project were either purchased from suppliers or obtained from Montana Tech's Native Plant Restoration Project in Butte, Montana. All of the seeds selected for use in this project are native to Butte (Anderson, 2014). Native species have greater possibility of long-term survival in the harsh rowing climate of Butte. Table VI lists the selected tree species for this project. Currently, seedlings of Sagebrush (*Artemisia tridentata*) and Quaking aspen (*Populus tremuloides*) have been planted. Seeds of choke cherry (*Prunus virginiana*) and

shrubby potentilla (*Potentilla fruticosa*) have sprouted and have been planted while mountain ash (*Sorbus sitchensis*) and douglas fir (*Pseudotsuga menziesii*) are still being stratified.

Table VI: Species of trees native to Butte, Montana used in the project

Species	Family	Status
Quaking aspen (<i>Populus tremuloides</i>)	Salicaceae	Planted
Douglas fir (<i>Pseudotsuga menziesii</i>)	Pinaceae	Under investigation
Canada red Choke Cherry (<i>Prunus virginiana</i>)	Bignoniaceae	Will be planted
Western mountain Ash (<i>Sorbus sitchensis</i>)	Rosaceae	Under investigation
Sagebrush (<i>Artemisia tridentata</i>)	Asteraceae	Planted
Shrubby potentilla (<i>Potentilla fruticosa</i>)	Rosaceae	Will be planted

4.3.1. Tree Growth

An initial attempt was made to plant the seeds directly into the soil and tailings without any pretreatment of the seeds or crushing of the soil and tailings samples. Two seeds for each tree species listed in Table VI except sagebrush (*Artemisia tridentata*) and shrubby potentilla (*Potentilla fruticosa*) were planted in four-inch pots, placed in a gazebo in the back yard of one of the project researchers, and watered daily with water totaling one inch per week (16 milliliters) during the summer of 2017. None of the seeds germinated. Failure was attributed to the coarse texture of the soil and tailings since most seeds do not grow well in gravelly soil. This led to a decision to crush and grind the tailings to a finer texture more capable of supporting seed germination and growth and also to pretreat the seeds before planting. The soils and tailings were ground to minus No. 14 US mesh size.

The stratification method of seed germination was adopted for pre-treatment of the seeds for growth. A peat moss and vermiculite mixture was prepared in equal ratios to serve as the initial growing medium for the seeds. Vermiculite is composed of hydrated laminar minerals (e.g. mica) which improves soil aeration and increases water and nutrient retention. Adding peat moss accelerates growth and promotes anchorage for tender young stems.

To soften the seeds and enhance sprouting, twenty-five seeds from each species were scarified and soaked in water, with the exception of the quaking aspen (*Populus tremuloides*) seeds, for approximately 24 hours before planting in the peat moss/vermiculite mixture. The mixture, with the seeds planted in them, was placed in a cheese cloth.

The seeds were refrigerated during the night and brought outside into an airy area intermittently during the day to vary temperature and allow them to be exposed to oxygen and light for germination. The seeds were watered once a day with an average of 45 milliliters (ml) of water for each set-up. Figure 8 shows an illustration of the stratification process.

Figure 8: Seed stratification mechanism

The success rate of this approach was very low as very few seeds showed signs of sprouting. It is believed that the low sprouting success was due to incorrect temperature regulation of the process.

Exposing evergreen seeds to temperatures between 7° and 13°C is ideal and actually helps to enhance sprouting (Hill, 1985). The peat moss/vermiculite mixture was kept moist and

refrigerated at a temperature averaging 7° C. Because native seeds sprout well with cold stratification, high sprouting rates were achieved with this constant temperature process. Keeping the seeds in a constant cold temperature without being exposed to high temperatures enhanced the sprouting of the seeds.

The seeds that sprouted were planted in three hundred and sixty (360), 1.5-inch diameter planting tubes in either a mixture of the peat moss/vermiculite medium (growing media control) or mine tailings. Sixty sprouted seeds of each species were planted in each of the five tailing samples and the potting mix. The total number of seeds planted is illustrated in Table VII.

Table VII: Number of seedlings planted

	Underground Greenhouse		Surface Greenhouse
	Potable water	Mine shaft water	
Sample 1	20	20	20
Sample 2	20	20	20
Sample 3	20	20	20
Sample 4	20	20	20
Sample 5	20	20	20
Potting Mix	20	20	20
Total	120	120	120
			360

Surface application of slow release fertilizer (Osmocote®) was added to the tailings before planting the sprouts. The planted sprouts were moved to the underground greenhouse to develop into healthy seedlings (Figure 9). An equal amount of plants in the underground greenhouse have been retained in a surface greenhouse on Montana Tech's campus to serve as a temperature control.

Figure 9: Seedlings growing in UMEC's underground greenhouse

4.3.2. Watering

The seedlings in the underground greenhouse are watered once a week with 10ml per seedling. The high humidity content in the greenhouse enables the seedlings to retain water needed for growth for a longer time than they would on the surface therefore, watering is only conducted once a week. A section of the seedlings are watered with mine shaft water which has a pH of 7.5 and another set (water control) is watered with 5ml of potable water each week.

4.4. Experimental Controls

Control factors were incorporated to determine if the results from growing seedlings in tailings and in using mine shaft water are viable in developing trees tolerable to degraded growing media. The controls include:

- Location (growing seedlings in the surface greenhouse);
- Mode of watering (watering seedlings with potable water); and,
- Growing medium (planting seedlings in potting mix).

Due to the unique conditions that exist in the underground greenhouse, another experiment for seedling growth was set up in the surface greenhouse, which is a traditional way of growing tree seedlings. This is to serve as a control mechanism by which growth rates of seeds in the underground greenhouse can be compared. The surface greenhouse operates at an average temperature of 20 °C and 65% humidity compared to the underground greenhouse at 7.5°C and 100% humidity. Figure 10 shows seedlings growing in the surface greenhouse while Figure 11 shows seedlings growing in the underground greenhouse.

Figure 10: Trees growing in surface greenhouse

Figure 11: Trees growing in UMEC's underground greenhouse

5. Data Analysis

5.1.1. Survival Rates

The project has recorded considerable seedling survival rates. Data collected shows most of the tree seedlings surviving in both the underground and surface greenhouses (control), in the tailings and in the potting mix (control), and when watered from both the mine shaft and potable water (control) sources.

Sagebrush seedlings planted in the potting mix in the surface greenhouse and underground greenhouse watered with potable water recorded 100% survival rates while those watered with mine shaft water in the underground greenhouse recorded a 60% survival rate. The average aspen seedling survival rates in sample 1 was 70% while sagebrush survival was 67%. The seedlings recorded good survival rates in all the soil samples except for sample 2 which recorded the overall lowest survival rates. The general survival rates of the seedlings can be found in Appendix A.

The survival rates appear to be comparable between seedlings in the underground greenhouse watered with mine shaft water and those watered with potable water. In sample 2 both recorded 35% survival rates and 0% in sample 2. The percentage difference in sample 1 and 4 was 5% in favor of the seedlings watered with mine shaft water. (Figure 12).

Figure 12: Comparison of survival rates between seedlings watered with potable water and mine shaft water

Tree seedling survival rates in the surface greenhouse and the underground greenhouse appears to be comparable in all the soil and tailing samples with the most difference recorded in the potting mix (Figure 13). This difference in seedling survival rates between the traditional surface greenhouse and the underground greenhouse is most likely insignificant and gives an indication of a successful operation in the underground greenhouse.

Figure 13: Comparison of survival rates between seedlings grown in underground greenhouse and seedlings grown on surface greenhouse

Sample 2, has the lowest recorded survival rate among all the growing media. This is probably due to the low pH (i.e. high acidity) of the tailings. Future project work will investigate to determine if Sample 2 can support tree seedlings when amendments are incorporated to adjust its pH. Table VIII presents the average survival rates of the seedlings in the soils and tailings.

Table VIII: Average survival rates

Specie	Sample Location	Survival Rate
	Sample 1	70%
	Sample 2	3%
Aspen	Sample 3	50%
	Sample 4	77%
	Sample 5	27%
	Potting Mix	53%
	Sample 1	67%
	Sample 2	0%
Sagebrush	Sample 3	17%
	Sample 4	50%
	Sample 5	43%
	Potting Mix	87%

Overall, 47% of the quaking aspens (*Populus tremuloides*) and 44% of the sagebrush (*Artemisia tridentata*) have survived. Samples 1, 4 and the potting mix show over 60% of the planted seedlings surviving. Sample 2 shows 2% of planted seedlings surviving. The potting mix (control) showed the highest survival rate of 70% of seedling growth (Table IX).

Table IX: Overall survival rates

Species	Overall Survival Rate
Aspen	47%
Sagebrush	44%
Soil Type	Overall Survival Rate
Sample 1	68%
Sample 2	2%
Sample 3	33%
Sample 4	63%
Sample 5	35%
Potting Mix	70%

5.1.2. Tree Growth Statistics

The heights of the seedlings are measured weekly to track growth rate. Appendix C shows the data for the weekly seedling heights in both the surface and underground greenhouses.

Seedlings growing in the underground greenhouse have averaged a height of 0.65cm for the seedlings being watered with mine shaft water and 1.08cm for the seedlings being watered with potable water. The seedlings growing in the surface greenhouse have averaged 1.75cm of growth (Table X).

Table X: Summary of seedling heights (cm)

	Underground greenhouse (Mine shaft water)	Underground greenhouse (Potable water)	Surface greenhouse
Sample 1	0.65	0.95	1.15
Sample 2	0.23		1.29
Sample 3	0.65	0.91	0.79
Sample 4	0.80	1.43	1.91
Sample 5	0.73	1.03	1.89
Potting mix	0.82	1.09	3.50
Overall average heights	0.65	1.08	1.75

Analysis of Variance (ANOVA) testing was employed to determine if there is evidence to suggest that there is significant difference between the mean heights of seedlings in the various soil samples and the planting locations at $\alpha = 0.10$. The factor, soil sample (1, 2, 3, 4, 5 and potting mix) was nested within factor, plant (aspen, sagebrush) and nested within factor type (surface, underground potable water, underground mine shaft water). This analysis produced a p-value < 0.001 . A calculated P-value that is less than or equal to α indicates that there is statistical difference between the mean values (Conrad, 2002). Thus, there is very strong evidence that the mean growths are not all equal.

Tukey's test was used to examining all pairwise differences in the means since the ANOVA test proved that there was significant difference in the mean values. Tukey's test was employed with a 95% simultaneous confidence level. Table (XI) presents a summary of the test conditions and their corresponding confidence intervals for the difference between means for aspen and sagebrush. The full analysis of the test can be found in Appendix B. The conclusions of evidence of significant differences or otherwise were based on the confidence intervals either consisting of all positive or negative values, or containing the number zero (0). For example; the confidence interval for the difference between means denoted by ASPEN: UGpot-Control: ASPEN: UGpot (Aspen UG potable water, tailings < Aspen UG potable water, potting soil) is given by -4.86, -1.15, gives the evidence that the mean growth for aspens seedlings planted in the mine tailings in the underground greenhouse and watered with potable water is less than the mean growth for aspens planted in the potting mix in the underground greenhouse and watered with potable water.

Table XI: Summary of analysis of variance of Tukey's testing

Pairwise test condition	Confidence Interval	Mean difference
ASPEN: UGpot-Control: ASPEN: UGpot	-4.86 -1.15	S
ASPEN: UGpot-Control: ASPEN: Surf	-2.64 0.00	S
ASPEN: Surf-Control: ASPEN: Surf	0.27 0.58	S
ASPEN: UGMP-Control: ASPEN: Surf	-0.18 0.00	NS
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGpot	-1.98 -1.09	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGpot	0.43 0.00	NS
SAGEBRUSH: Surf-Control: SAGEBRUSH: Surf	0.55 0.00	NS

S – Significant

NS – Not Significant

UGMP – Underground greenhouse mine shaft water

UGpot – Underground greenhouse potable water

Surf – Surface greenhouse

The results of the ANOVA and Tukey's tests indicate significant differences in average heights between the surface grown and underground grown seedlings. These differences are

expected since the seedlings are in their early stages of growth. The differences in seedling growth heights may also be due to the differences in average greenhouse temperature (7.5° C underground versus 20° C surface). Tree heights will continue to be monitored to further determine if there is a difference in growth.

6. Conclusions

The underground greenhouse is serving as a pilot system and incubator for developing seeds into healthy tree seedlings. The progression of preparing seedlings for planting is a staged process requiring year-round operation. When planting trees, knowledge of the optimal season (i.e. time) for planting is advantageous for growth success. In an underground greenhouse, multiple staging cycles can be in play at any given time, facilitating year-round use of the facility. Although traditional greenhouse growing conditions provided significantly better survival and growth rate results, the plants in the underground greenhouse were comparable to the surface greenhouse.

It is believed that trees grown in an underground greenhouse will cost less and can be specifically tailored to successfully grow in the harsh Butte environment. It is also expected that there will be lower development and maintenance costs (Wood/steel framing, HVAC systems for temperature and humidity regulation, etc.) associated with an underground greenhouse as compared to the traditional surface greenhouse. This makes growing trees in the underground greenhouse, for this project, less expensive than purchasing trees from, say, the Montana State nursery. The successful development of the underground greenhouse and the high survival rates of tree seedlings, so far, suggest that it is a viable approach to economically propagate healthy trees in Butte. It is anticipated that the final outcome of this project will result in significantly improved reclamation of the BASFS through tree growth leading in improved and maintained water quality in Silver Bow Creek and within Butte Area One.

7. Future Work

As the tree seedlings grow larger, they will be transplanted to two-inch and then to four-inch pots and treated (hardened) into healthy seedlings to be planted in Butte. Investigations will also be conducted into adjusting the pH of the tailings by addition of sewage sludge or lime to provide a low-cost solution to enable sustainable seedling growth.

Future work will also focus on detailed investigations into the cost components of constructing and operating an underground greenhouse and a surface greenhouse.

As the seedlings grow further, it may become necessary to transplant them to six-inch pots to get them ready for planting in the BASFS. Tree seedling will be hardened in a semi-sheltered environment at the UMEC for approximately two months before they will be transported to the BASFS.

Tree planting on the tailing sites will be performed using project personnel, collaborators, and volunteer labor. The slit method of planting seedlings using a planting bar, shovel, or spade, to create a vertical slit in the tailings will be used. Planting density will be predetermined to prevent overcrowding the seedlings.

The project will be considered to be a success if at least 50 percent of the seedlings survive growing in tailings in the BASFS after two years of planting, as tree growth stabilizes by the end of the second growing season for most reclamation methods (Conrad, 2002).

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9. Appendix A: General seedling survival rates

Table XII: General seedling survival rates

Degraded Soils in underground greenhouse (Potable water)			Degraded Soils in underground greenhouse (Mine shaft water)			Degraded soils in surface greenhouse			Average Survival (Soil Type)
	Sample 1	30%		Sample 1	90%		Sample 1	90%	70%
	Sample 2	0%		Sample 2	0%		Sample 2	10%	3%
	Sample 3	50%		Sample 3	60%		Sample 3	40%	50%
Aspen	Sample 4	70%	Aspen	Sample 4	60%	Aspen	Sample 4	100%	77%
	Sample 5	30%		Sample 5	50%		Sample 5	0%	27%
	Potting Mix	40%		Potting Mix	50%		Potting Mix	70%	53%
	Sample 1	90%		Sample 1	60%		Sample 1	50%	67%
Sagebrush	Sample 2	0%	Sagebrush	Sample 2	0%	Sagebrush	Sample 2	0%	0%
	Sample 3	20%		Sample 3	10%		Sample 3	20%	17%
	Sample 4	90%		Sample 4	30%		Sample 4	30%	50%
	Sample 5	40%		Sample 5	30%		Sample 5	60%	43%
	Potting Mix	100%		Potting Mix	60%		Potting Mix	100%	87%

10. Appendix B: Test results of significant difference for analysis of variance by Tukey's testing for aspens and sagebrush

Pairwise test condition	Confidence Interval	Mean difference
Sagebrush		
Sample 1		
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGpot	-1.88 -1.08	S
SAGEBRUSH: Surf-Control: SAGEBRUSH: Surf	-1.65 0.00	S
SAGEBRUSH: UGMP-Control: SAGEBRUSH: Surf	-2.19 0.00	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: Surf	-1.61 0.00	S
SAGEBRUSH: UGMP-Control: SAGEBRUSH:UGMP	0.62 1.00	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGMP	1.20 0.10	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGpot	0.7 1.00	S
Sample 2		
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGpot	-1.33 -2.22	S
SAGEBRUSH: Surf-Control: SAGEBRUSH: Surf	-2.78 0.00	S
SAGEBRUSH: UGMP-Control: SAGEBRUSH: Surf	-2.75 0.00	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: Surf	-2.75 0.00	S
SAGEBRUSH: UGMP-Control: SAGEBRUSH: UGMP	0.06 0.12	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGMP	0.06 0.12	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGpot	-0.43 0.00	NS
Sample 3		
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGpot	-1.98 -1.09	S
SAGEBRUSH: Surf-Control: SAGEBRUSH: Surf	-2.00 0.00	S
SAGEBRUSH: UGMP-Control: SAGEBRUSH: Surf	-2.22 0.00	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: Surf	-1.62 0.00	S
SAGEBRUSH: UGMP-Control: SAGEBRUSH: UGMP	0.59 1.00	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGMP	1.19 1.00	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGpot	0.70 1.00	S
Sample 4		
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGpot	5.14 -0.38	S
SAGEBRUSH: Surf-Control: SAGEBRUSH: Surf	-1.11 0.00	S
SAGEBRUSH:UGMP-Control: SAGEBRUSH: Surf	-1.93 0.00	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: Sur	-0.91 0.00	NS
SAGEBRUSH: UGMP-Control: SAGEBRUSH: UGMP	0.88 1.00	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGM	1.90 0.00	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGpot	1.41 0.97	S
Sample 5		
SAGEBRUSH: UGpot-Control: SAGBRUSH: UGpot	6.50 -0.83	S
SAGEBRUSH: Surf-Control: SAGEBRUSH: Surf	-0.55 0.00	NS
SAGEBRUSH: UGMP-Control: SAGEBRUSH: Surf	-2.02 0.00	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: Surf	-1.36 0.00	S
SAGEBRUSH: UGMP-Control: SAGEBRUSH: UGMP	0.79 1.00	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGMP	1.4 0.78	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGpot	0.96 1.00	S
Potting mix (Control)		
SAGEBRUSH: UGMP-Control: SAGEBRUSH: Surf	-1.98 0.00	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: Surf	-1.42 0.00	S
SAGEBRUSH: UGpot-Control: SAGEBRUSH: UGMP	1.39 0.93	S

Pairwise test condition	Confidence Interval	Mean difference
Aspen		
Sample 1		
ASPEN: UGpot-Control: ASPEN: UGpot	-4.86 -1.15	S
ASPEN: UGpot-Control: ASPEN: UGpot	-1.30 -1.22	S
ASPEN: Surf-Control: ASPEN: Surf	-2.27 0.00	S
ASPEN: UGMP-Control: ASPEN: Surf	-2.72 0.00	S
ASPEN: UGpot-Control: ASPEN: Surf	-2.64 0.00	S
ASPEN: Surf-Control: ASPEN: Surf	0.27 0.58	S
ASPEN: UGMP-Control: ASPEN: Surf	-0.18 0.00	NS
ASPEN: UGpot-Control: ASPEN: Sur	-0.10 0.01	NS
ASPEN: UGMP-Control: ASPEN: UGMP	0.71 1.00	S
ASPEN: UGpot-Control: ASPEN: UGMP	0.79 1.00	S
ASPEN: UGpot-Control: ASPEN: UGpot	1.05 1.00	S
ASPEN: UGpot-Control: ASPEN: UGpot	0.97 1.00	S
Sample 2		
ASPEN: UGpot-Control: ASPEN: UGpot	-8.18 -1.92	S
ASPEN: UGpot-Control: ASPEN: UGpot	-9.00 -1.99	S
ASPEN: Surf-Control: ASPEN: Surf	-2.15 0.00	S
ASPEN: UGMP-Control: ASPEN: Surf	-3.36 0.00	S
ASPEN: UGpot-Control: ASPEN: Surf	-3.41 0.00	S
ASPEN: Surf-Control: ASPEN: Surf	0.39 0.87	S
ASPEN: UGMP-Control: ASPEN: Surf	-0.82 0.00	NS
ASPEN: UGpot-Control: ASPEN: Surf	-0.87 0.00	NS
ASPEN: UGMP-Control: ASPEN: UGMP	0.07 0.13	S
ASPEN: UGpot-Control: ASPEN: UGMP	0.02 0.07	S
ASPEN: UGpot-Control: ASPEN: UGpot	0.28 0.58	S
ASPEN: UGpot-Control: ASPEN: UGpot	0.19 0.35	S
Sample 3		
ASPEN: UGpot-Control: ASPEN: UGpot	-1.17 -1.2	S
ASPEN: UGpot-Control: ASPEN: UGpot	-1.98 -1.30	S
ASPEN: Surf-Control: ASPEN: Surf	-2.64 0.00	S
ASPEN: UGMP-Control: ASPEN: Surf	-2.70 0.00	S
ASPEN: UGpot-Control: ASPEN: Surf	-2.71 0.00	S
ASPEN: Surf-Control: ASPEN: Surf	-0.10 0.01	NS
ASPEN: UGMP-Control: ASPEN: Surf	-0.16 0.01	NS
ASPEN: UGpot-Control: ASPEN: Surf	-0.17 0.01	NS
ASPEN: UGMP-Control: ASPEN: UGMP	0.72 1.00	S
ASPEN: UGpot-Control: ASPEN: UGpot	0.98 1.00	S
ASPEN: UGpot-Control: ASPEN: UGpot	0.90 1.00	S

Pairwise test condition	Confidence Interval	Mean difference
Aspen		
Sample 4		
ASPEN: UGpot-Control: ASPEN: UGpot	2.03 -0.90	S
ASPEN: UGpot-Control: ASPEN: UGpot	1.21 -0.98	S
ASPEN: Surf-Control: ASPEN: Surf	-1.29 0.00	S
ASPEN: UGMP-Control: ASPEN: Surf	-2.68 0.00	S
ASPEN: UGpot-Control: ASPEN: Surf	-2.39 0.00	S
ASPEN: Surf-Control: ASPEN: Surf	1.25 1.00	S
ASPEN: UGMP-Control: ASPEN: Surf	-0.14 0.01	NS
ASPEN: UGpot-Control: ASPEN: Surf	0.15 0.23	S
ASPEN: UGMP-Control: ASPEN: UGMP	0.75 1.00	S
ASPEN: UGpot-Control: ASPEN: UGMP	1.05 1.00	S
ASPEN: UGpot-Control: ASPEN: UGpot	1.30 1.00	S
ASPEN: UGpot-Control: ASPEN: UGpot	1.22 1.00	S
Sample 5		
ASPEN: UGpot-Control: ASPEN: UGpot	-1.41 -1.24	S
ASPEN: UGpot-Control: ASPEN: UGpot	-2.22 -1.32	S
ASPEN: Surf-Control: ASPEN: Surf	-1.89 0.00	S
ASPEN: UGMP-Control: ASPEN: Surf	-2.74 0.00	S
ASPEN: UGpot-Control: ASPEN: Surf	-2.73 0.00	S
ASPEN: Surf-Control: ASPEN: Surf	0.65 0.99	S
ASPEN: UGMP-Control: ASPEN: Surf	-0.20 0.00	NS
ASPEN: UGpot-Control: ASPEN: Surf	-0.19 0.00	NS
ASPEN: UGMP-Control: ASPEN: UGMP	0.69 1.00	S
ASPEN: UGpot-Control: ASPEN: UGMP	0.70 1.00	S
ASPEN: UGpot-Control: ASPEN: UGpot	0.96 1.00	S
ASPEN: UGpot-Control: ASPEN: UGpot	0.86 1.00	S
Potting mix (Control)		
ASPEN: UGpot-Control: ASPEN: UGpot	8.17 -1.19	S
ASPEN: Surf-Control: ASPEN: Surf	-1.25 0.00	S
ASPEN: UGMP-Control: ASPEN: Surf	-2.60 0.00	S
ASPEN: UGpot-Control: ASPEN: Surf	-2.33 0.00	S
ASPEN: UGMP-Control: ASPEN: Surf	-0.06 0.02	NS
ASPEN: UGpot-Control: ASPEN: Surf	0.20 0.28	S
ASPEN: UGpot-Control: ASPEN: UGMP	1.05 1.00	S
ASPEN:UGpot-Control:ASPEN:UGpot	1.35 1.00	S

11. Appendix C: Weekly seedling height data

			PLANT 1	PLANT 2	PLANT 3	PLANT 4	PLANT 5	PLANT 6	PLANT 7	PLANT 8	PLANT 9	PLANT 10
WEEK 1	ASPEN	SS1	0.9	0.3	0.7	1.1	0.9	0.4	0.9	0.2	0.8	0.6
		SS2	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.3	0.0
		SS3	1.2	0.6	0.3	0.2	0.7	0.5	0.7	0.6	1.1	0.7
		SS4	0.9	0.9	0.4	1.0	0.3	0.0	1.1	0.6	0.8	1.2
		SS5	0.4	1.0	0.9	1.1	0.7	0.4	0.7	0.5	0.8	1.2
		Potting mix	0.6	1.1	0.9	0.6	0.8	0.0	1.1	0.8	0.0	1.0
	SAGEBRUSH	SS1	0.0	0.7	0.1	0.3	0.1	0.3	0.4	0.3	0.2	0.1
		SS2	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
		SS3	1.9	0.1	0.0	0.3	0.3	0.0	0.3	0.1	0.2	0.3
		SS4	0.2	0.3	0.2	0.3	0.1	0.0	0.7	0.3	1.2	0.0
		SS5	0.3	0.2	0.4	0.1	0.2	1.0	0.1	0.4	0.2	0.0
		Potting mix	0.3	0.6	1.0	0.5	0.6	0.3	0.5	1.1	0.0	0.0
WEEK 2	ASPEN	SS1	1.1	0.6	0.9	1.3	0.9	0.5	1.0	0.0	0.7	0.6
		SS2	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
		SS3	1.3	0.7	0.5	0.6	0.5	0.7	0.9	0.8	0.9	0.4
		SS4	0.9	1.2	0.5	1.2	0.3	0.0	1.1	0.6	0.9	1.2
		SS5	0.9	1.0	1.0	0.8	0.6	0.6	0.6	0.9	1.3	0.7
		Potting mix	1.0	0.9	1.1	0.6	0.7	0.0	1.0	0.9	0.0	1.3
	SAGEBRUSH	SS1	0.6	0.0	0.3	0.1	0.5	0.2	0.6	0.4	0.4	0.8
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.7	0.0	0.0	0.6	0.2	0.0	0.5	0.0	0.0	0.0
		SS4	0.5	0.7	0.4	0.5	0.5	1.0	0.7	0.0	1.3	0.3
		SS5	0.7	0.2	0.7	0.0	0.6	1.1	0.8	0.9	0.0	0.0
		Potting mix	0.8	1.1	1.1	0.6	0.7	1.0	0.6	1.1	0.0	0.0
WEEK 3	ASPEN	SS1	1.1	0.2	0.8	1.2	0.9	0.3	1.2	0.0	0.6	0.6
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.3	0.7	0.4	0.0	0.6	0.4	1.0	0.9	0.7	0.3
		SS4	1.2	1.0	0.6	0.7	0.5	0.0	1.1	0.6	1.0	0.9
		SS5	0.7	0.8	0.5	0.7	0.4	0.5	0.6	1.0	1.3	0.4
		Potting mix	0.7	0.9	0.7	0.6	0.8	0.0	0.9	1.2	0.0	0.7
	SAGEBRUSH	SS1	0.9	0.0	0.6	0.4	0.7	0.0	0.5	0.0	0.0	0.8
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.6	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
		SS4	0.0	0.0	0.6	0.7	2.6	1.1	1.0	0.0	1.6	0.0
		SS5	0.0	0.0	0.7	0.0	0.6	1.2	0.0	0.0	0.0	0.0
		Potting mix	0.5	0.9	0.7	0.8	1.0	0.8	0.6	1.0	0.0	0.0
WEEK 4	ASPEN	SS1	1.0	0.4	0.8	1.2	0.9	0.5	1.0	0.0	0.6	0.7
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.2	0.8	0.5	0.0	0.6	0.6	0.8	0.9	0.7	0.3
		SS4	0.8	1.1	0.4	1.0	0.5	0.0	0.6	0.5	1.2	0.9
		SS5	0.6	0.9	0.6	0.9	0.6	0.5	0.0	1.2	1.3	0.4
		Potting mix	0.7	1.0	1.2	0.8	0.7	0.0	1.2	0.6	0.0	1.2
	SAGEBRUSH	SS1	0.8	0.0	0.5	0.3	0.7	0.0	0.4	0.0	0.0	1.0
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.0	0.0	0.0	0.7	0.0	0.0	0.5	0.0	0.0	0.0
		SS4	0.0	0.0	0.7	0.5	0.7	0.8	1.0	0.0	1.6	0.0
		SS5	0.0	0.0	0.7	0.0	0.7	0.9	0.0	0.0	0.0	0.0
		Potting mix	0.7	0.0	1.1	0.9	0.6	1.0	0.6	0.9	1.2	0.0
WEEK 5	ASPEN	SS1	0.9	0.4	0.7	0.9	0.7	0.3	0.6	0.0	0.8	0.8
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.0	0.8	0.4	0.0	0.6	0.0	0.8	1.0	0.6	0.0
		SS4	0.7	0.9	0.2	0.8	0.0	0.0	0.8	0.6	0.6	0.9
		SS5	0.7	0.0	0.0	0.7	0.6	0.5	0.0	0.7	1.4	0.5
		Potting mix	0.6	0.7	1.3	0.8	0.6	0.0	1.2	0.0	0.0	0.7
	SAGEBRUSH	SS1	0.8	0.0	0.7	0.5	0.8	0.0	0.7	0.0	0.0	1.1
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
		SS4	0.0	0.0	0.0	0.6	0.7	0.7	0.9	0.9	0.0	1.7
		SS5	0.0	0.7	0.0	0.8	1.0	0.0	0.0	0.0	2.0	0.0
		Potting mix	0.5	0.8	1.2	0.8	0.5	0.9	0.7	0.6	1.3	0.0
WEEK 6	ASPEN	SS1	1.0	0.0	0.6	0.7	0.6	0.3	0.7	0.0	0.3	0.3
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.7	1.1	0.0	0.0	0.5	0.0	0.4	0.9	0.6	0.0
		SS4	0.6	0.5	0.0	0.9	0.0	0.0	0.8	0.4	0.6	0.0
		SS5	0.0	0.0	0.0	0.5	0.0	0.5	0.0	0.7	1.3	0.4
		Potting mix	0.7	0.7	0.9	0.5	0.0	0.0	1.1	0.0	0.0	0.0
	SAGEBRUSH	SS1	0.6	0.0	0.8	0.3	0.8	0.0	0.0	0.0	1.1	0.5
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0
		SS4	0.0	0.0	0.5	0.5	0.8	0.0	0.8	0.0	1.6	0.0
		SS5	0.0	0.0	0.6	0.0	0.9	1.1	0.0	0.0	0.0	0.0
		Potting mix	0.6	0.7	1.0	0.7	0.0	0.9	0.7	0.9	1.2	0.0
WEEK 7	ASPEN	SS1	1.1	0.5	0.7	1.0	1.1	0.3	0.7	0.0	0.4	0.4
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.8	0.7	0.0	0.0	0.6	0.0	1.7	0.8	0.8	0.0
		SS4	0.7	0.8	0.0	0.6	0.0	0.0	0.8	0.4	0.7	0.0
		SS5	0.0	0.0	0.0	0.6	0.0	0.2	0.0	0.6	0.1	0.5
		Potting mix	0.7	0.6	0.8	0.5	0.0	0.0	1.0	0.0	0.0	0.0
	SAGEBRUSH	SS1	0.5	0.0	0.9	0.4	0.7	0.0	0.6	0.0	0.0	1.2
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
		SS4	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	1.7	0.0
		SS5	0.0	0.0	0.4	0.0	0.7	1.1	0.0	0.0	0.0	0.0
		Potting mix	0.6	0.0	1.2	0.6	0.0	0.8	0.9	0.7	0.0	0.0

Figure 14: Weekly seedling height data of plants in underground greenhouse watered with mine shaft water (SS1-SS5=Soil sample 1-5)

			PLANT 1	PLANT 2	PLANT 3	PLANT 4	PLANT 5	PLANT 6	PLANT 7	PLANT 8	PLANT 9	PLANT 10
WEEK 1	ASPEN	SS1	0.9	0.3	0.7	1.1	0.9	0.4	0.9	0.2	0.8	0.6
		SS2	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.3	0.0
		SS3	1.2	0.6	0.3	0.2	0.7	0.5	0.7	0.6	1.1	0.7
		SS4	0.9	0.9	0.4	1.0	0.3	0.0	1.1	0.6	0.8	1.2
		SS5	0.4	1.0	0.9	1.1	0.7	0.4	0.7	0.5	0.8	1.2
		Potting mix	0.6	1.1	0.9	0.6	0.8	0.0	1.1	0.8	0.0	1.0
WEEK 2	SAGEBRUSH	SS1	0.0	0.7	0.1	0.3	0.1	0.3	0.4	0.3	0.2	0.1
		SS2	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
		SS3	1.9	0.1	0.0	0.3	0.3	0.0	0.3	0.1	0.2	0.3
		SS4	0.2	0.3	0.2	0.3	0.1	0.0	0.7	0.3	1.2	0.0
		SS5	0.3	0.2	0.4	0.1	0.2	1.0	0.1	0.4	0.2	0.0
		Potting mix	0.3	0.6	1.0	0.5	0.6	0.3	0.5	1.1	0.0	0.0
WEEK 3	ASPEN	SS1	1.1	0.6	0.9	1.3	0.9	0.5	1.0	0.0	0.7	0.6
		SS2	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
		SS3	1.3	0.7	0.5	0.6	0.5	0.7	0.9	0.8	0.9	0.4
		SS4	0.9	1.2	0.5	1.2	0.3	0.0	1.1	0.6	0.9	1.2
		SS5	0.9	1.0	1.0	0.8	0.6	0.6	0.6	0.9	1.3	0.7
		Potting mix	1.0	0.9	1.1	0.6	0.7	0.0	1.0	0.9	0.0	1.3
WEEK 4	SAGEBRUSH	SS1	0.6	0.0	0.3	0.1	0.5	0.2	0.6	0.4	0.4	0.8
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.7	0.0	0.0	0.6	0.2	0.0	0.5	0.0	0.0	0.0
		SS4	0.5	0.7	0.4	0.5	0.5	1.0	0.7	0.0	1.3	0.3
		SS5	0.7	0.2	0.7	0.0	0.6	1.1	0.8	0.9	0.0	0.0
		Potting mix	0.8	1.1	1.1	0.6	0.7	1.0	0.6	1.1	0.0	0.0
WEEK 5	ASPEN	SS1	1.1	0.2	0.8	1.2	0.9	0.3	1.2	0.0	0.6	0.6
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.3	0.7	0.4	0.0	0.6	0.4	1.0	0.9	0.7	0.3
		SS4	1.2	1.0	0.6	0.7	0.5	0.0	1.1	0.6	1.0	0.9
		SS5	0.7	0.8	0.5	0.7	0.4	0.5	0.6	1.0	1.3	0.4
		Potting mix	0.7	0.9	0.7	0.6	0.8	0.0	0.9	1.2	0.0	0.7
WEEK 6	SAGEBRUSH	SS1	0.9	0.0	0.6	0.4	0.7	0.0	0.5	0.0	0.0	0.8
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.6	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
		SS4	0.0	0.0	0.6	0.7	2.6	1.1	1.0	0.0	1.6	0.0
		SS5	0.0	0.0	0.7	0.0	0.6	1.2	0.0	0.0	0.0	0.0
		Potting mix	0.5	0.9	0.7	0.8	1.0	0.8	0.6	1.0	0.0	0.0
WEEK 7	ASPEN	SS1	1.0	0.4	0.8	1.2	0.9	0.5	1.0	0.0	0.6	0.7
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.2	0.8	0.5	0.0	0.6	0.6	0.8	0.9	0.7	0.3
		SS4	0.8	1.1	0.4	1.0	0.5	0.0	0.6	0.5	1.2	0.9
		SS5	0.6	0.9	0.6	0.9	0.6	0.5	0.0	1.2	1.3	0.4
		Potting mix	0.7	1.0	1.2	0.8	0.7	0.0	1.2	0.6	0.0	1.2
WEEK 8	SAGEBRUSH	SS1	0.8	0.0	0.5	0.3	0.7	0.0	0.4	0.0	0.0	1.0
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.0	0.0	0.0	0.7	0.0	0.0	0.5	0.0	0.0	0.0
		SS4	0.0	0.0	0.7	0.5	0.7	0.8	1.0	0.0	1.6	0.0
		SS5	0.0	0.0	0.7	0.0	0.7	0.9	0.0	0.0	0.0	0.0
		Potting mix	0.7	0.0	1.1	0.9	0.6	1.0	0.6	0.9	1.2	0.0
WEEK 9	ASPEN	SS1	0.9	0.4	0.7	0.9	0.7	0.3	0.6	0.0	0.8	0.8
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.0	0.8	0.4	0.0	0.6	0.0	0.8	1.0	0.6	0.0
		SS4	0.7	0.9	0.2	0.8	0.0	0.0	0.8	0.6	0.6	0.9
		SS5	0.7	0.0	0.0	0.7	0.6	0.5	0.0	0.7	1.4	0.5
		Potting mix	0.6	0.7	1.3	0.8	0.6	0.0	1.2	0.0	0.0	0.7
WEEK 10	SAGEBRUSH	SS1	0.8	0.0	0.7	0.5	0.8	0.0	0.7	0.0	0.0	1.1
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
		SS4	0.0	0.0	0.0	0.6	0.7	0.7	0.9	0.9	0.0	1.7
		SS5	0.0	0.7	0.0	0.8	1.0	0.0	0.0	0.0	2.0	0.0
		Potting mix	0.5	0.8	1.2	0.8	0.5	0.9	0.7	0.6	1.3	0.0
WEEK 11	ASPEN	SS1	1.0	0.0	0.6	0.7	0.6	0.3	0.7	0.0	0.3	0.3
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.7	1.1	0.0	0.0	0.5	0.0	0.4	0.9	0.6	0.0
		SS4	0.6	0.5	0.0	0.9	0.0	0.0	0.8	0.4	0.6	0.0
		SS5	0.0	0.0	0.0	0.5	0.0	0.5	0.0	0.7	1.3	0.4
		Potting mix	0.7	0.7	0.9	0.5	0.0	0.0	1.1	0.0	0.0	0.0
WEEK 12	SAGEBRUSH	SS1	0.6	0.0	0.8	0.3	0.8	0.0	0.0	0.0	1.1	0.5
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0
		SS4	0.0	0.0	0.5	0.5	0.8	0.0	0.8	0.0	1.6	0.0
		SS5	0.0	0.0	0.6	0.0	0.9	1.1	0.0	0.0	0.0	0.0
		Potting mix	0.6	0.7	1.0	0.7	0.0	0.9	0.7	0.9	1.2	0.0
WEEK 13	ASPEN	SS1	1.1	0.5	0.7	1.0	1.1	0.3	0.7	0.0	0.4	0.4
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.8	0.7	0.0	0.0	0.6	0.0	1.7	0.8	0.8	0.0
		SS4	0.7	0.8	0.0	0.6	0.0	0.0	0.8	0.4	0.7	0.0
		SS5	0.0	0.0	0.0	0.6	0.0	0.2	0.0	0.6	0.1	0.5
		Potting mix	0.7	0.6	0.8	0.5	0.0	0.0	1.0	0.0	0.0	0.0
WEEK 14	SAGEBRUSH	SS1	0.5	0.0	0.9	0.4	0.7	0.0	0.6	0.0	0.0	1.2
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
		SS4	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	1.7	0.0
		SS5	0.0	0.0	0.4	0.0	0.7	1.1	0.0	0.0	0.0	0.0
		Potting mix	0.6	0.0	1.2	0.6	0.0	0.8	0.9	0.7	0.0	0.0

Figure 15: Weekly seedling height data for plants in surface greenhouse

			PLANT 1	PLANT 2	PLANT 3	PLANT 4	PLANT 5	PLANT 6	PLANT 7	PLANT 8	PLANT 9	PLANT 10
WEEK 1	ASPEN	SS1	0.9	0.3	0.7	1.1	0.9	0.4	0.9	0.2	0.8	0.6
		SS2	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.3	0.0
		SS3	1.2	0.6	0.3	0.2	0.7	0.5	0.7	0.6	1.1	0.7
		SS4	0.9	0.9	0.4	1.0	0.3	0.0	1.1	0.6	0.8	1.2
		SS5	0.4	1.0	0.9	1.1	0.7	0.4	0.7	0.5	0.8	1.2
		Potting mix	0.6	1.1	0.9	0.6	0.8	0.0	1.1	0.8	0.0	1.0
	SAGEBRUSH	SS1	0.0	0.7	0.1	0.3	0.1	0.3	0.4	0.3	0.2	0.1
		SS2	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
		SS3	1.9	0.1	0.0	0.3	0.3	0.0	0.3	0.1	0.2	0.3
		SS4	0.2	0.3	0.2	0.3	0.1	0.0	0.7	0.3	1.2	0.0
		SS5	0.3	0.2	0.4	0.1	0.2	1.0	0.1	0.4	0.2	0.0
		Potting mix	0.3	0.6	1.0	0.5	0.6	0.3	0.5	1.1	0.0	0.0
WEEK 2	ASPEN	SS1	1.1	0.6	0.9	1.3	0.9	0.5	1.0	0.0	0.7	0.6
		SS2	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
		SS3	1.3	0.7	0.5	0.6	0.5	0.7	0.9	0.8	0.9	0.4
		SS4	0.9	1.2	0.5	1.2	0.3	0.0	1.1	0.6	0.9	1.2
		SS5	0.9	1.0	1.0	0.8	0.6	0.6	0.6	0.9	1.3	0.7
		Potting mix	1.0	0.9	1.1	0.6	0.7	0.0	1.0	0.9	0.0	1.3
	SAGEBRUSH	SS1	0.6	0.0	0.3	0.1	0.5	0.2	0.6	0.4	0.4	0.8
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.7	0.0	0.0	0.6	0.2	0.0	0.5	0.0	0.0	0.0
		SS4	0.5	0.7	0.4	0.5	0.5	1.0	0.7	0.0	1.3	0.3
		SS5	0.7	0.2	0.7	0.0	0.6	1.1	0.8	0.9	0.0	0.0
		Potting mix	0.8	1.1	1.1	0.6	0.7	1.0	0.6	1.1	0.0	0.0
WEEK 3	ASPEN	SS1	1.1	0.2	0.8	1.2	0.9	0.3	1.2	0.0	0.6	0.6
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.3	0.7	0.4	0.0	0.6	0.4	1.0	0.9	0.7	0.3
		SS4	1.2	1.0	0.6	0.7	0.5	0.0	1.1	0.6	1.0	0.9
		SS5	0.7	0.8	0.5	0.7	0.4	0.5	0.6	1.0	1.3	0.4
		Potting mix	0.7	0.9	0.7	0.6	0.8	0.0	0.9	1.2	0.0	0.7
	SAGEBRUSH	SS1	0.9	0.0	0.6	0.4	0.7	0.0	0.5	0.0	0.0	0.8
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.6	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
		SS4	0.0	0.0	0.6	0.7	2.6	1.1	1.0	0.0	1.6	0.0
		SS5	0.0	0.0	0.7	0.0	0.6	1.2	0.0	0.0	0.0	0.0
		Potting mix	0.5	0.9	0.7	0.8	1.0	0.8	0.6	1.0	0.0	0.0
WEEK 4	ASPEN	SS1	1.0	0.4	0.8	1.2	0.9	0.5	1.0	0.0	0.6	0.7
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.2	0.8	0.5	0.0	0.6	0.6	0.8	0.9	0.7	0.3
		SS4	0.8	1.1	0.4	1.0	0.5	0.0	0.6	0.5	1.2	0.9
		SS5	0.6	0.9	0.6	0.9	0.6	0.5	0.0	1.2	1.3	0.4
		Potting mix	0.7	1.0	1.2	0.8	0.7	0.0	1.2	0.6	0.0	1.2
	SAGEBRUSH	SS1	0.8	0.0	0.5	0.3	0.7	0.0	0.4	0.0	0.0	1.0
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.0	0.0	0.0	0.7	0.0	0.0	0.5	0.0	0.0	0.0
		SS4	0.0	0.0	0.7	0.5	0.7	0.8	1.0	0.0	1.6	0.0
		SS5	0.0	0.0	0.7	0.0	0.7	0.9	0.0	0.0	0.0	0.0
		Potting mix	0.7	0.0	1.1	0.9	0.6	1.0	0.6	0.9	1.2	0.0
WEEK 5	ASPEN	SS1	0.9	0.4	0.7	0.9	0.7	0.3	0.6	0.0	0.8	0.8
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	1.0	0.8	0.4	0.0	0.6	0.0	0.8	1.0	0.6	0.0
		SS4	0.7	0.9	0.2	0.8	0.0	0.0	0.8	0.6	0.6	0.9
		SS5	0.7	0.0	0.0	0.7	0.6	0.5	0.0	0.7	1.4	0.5
		Potting mix	0.6	0.7	1.3	0.8	0.6	0.0	1.2	0.0	0.0	0.7
	SAGEBRUSH	SS1	0.8	0.0	0.7	0.5	0.8	0.0	0.7	0.0	0.0	1.1
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
		SS4	0.0	0.0	0.0	0.6	0.7	0.7	0.9	0.9	0.0	1.7
		SS5	0.0	0.7	0.0	0.8	1.0	0.0	0.0	0.0	2.0	0.0
		Potting mix	0.5	0.8	1.2	0.8	0.5	0.9	0.7	0.6	1.3	0.0
WEEK 6	ASPEN	SS1	1.0	0.0	0.6	0.7	0.6	0.3	0.7	0.0	0.3	0.3
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.7	1.1	0.0	0.0	0.5	0.0	0.4	0.9	0.6	0.0
		SS4	0.6	0.5	0.0	0.9	0.0	0.0	0.8	0.4	0.6	0.0
		SS5	0.0	0.0	0.0	0.5	0.0	0.5	0.0	0.7	1.3	0.4
		Potting mix	0.7	0.7	0.9	0.5	0.0	0.0	1.1	0.0	0.0	0.0
	SAGEBRUSH	SS1	0.6	0.0	0.8	0.3	0.8	0.0	0.0	0.0	1.1	0.5
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0
		SS4	0.0	0.0	0.5	0.5	0.8	0.0	0.8	0.0	1.6	0.0
		SS5	0.0	0.0	0.6	0.0	0.9	1.1	0.0	0.0	0.0	0.0
		Potting mix	0.6	0.7	1.0	0.7	0.0	0.9	0.7	0.9	1.2	0.0
WEEK 7	ASPEN	SS1	1.1	0.5	0.7	1.0	1.1	0.3	0.7	0.0	0.4	0.4
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.8	0.7	0.0	0.0	0.6	0.0	1.7	0.8	0.8	0.0
		SS4	0.7	0.8	0.0	0.6	0.0	0.0	0.8	0.4	0.7	0.0
		SS5	0.0	0.0	0.0	0.6	0.0	0.2	0.0	0.6	0.1	0.5
		Potting mix	0.7	0.6	0.8	0.5	0.0	0.0	1.0	0.0	0.0	0.0
	SAGEBRUSH	SS1	0.5	0.0	0.9	0.4	0.7	0.0	0.6	0.0	0.0	1.2
		SS2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		SS3	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
		SS4	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	1.7	0.0
		SS5	0.0	0.0	0.4	0.0	0.7	1.1	0.0	0.0	0.0	0.0
		Potting mix	0.6	0.0	1.2	0.6	0.0	0.8	0.9	0.7	0.0	0.0

Figure 16: Weekly seedling height data of plants in underground greenhouse watered with potable water

SIGNATURE PAGE

This is to certify that the thesis prepared by Cosmas Opoku-Ware entitled "Developing Trees Tolerant to Degraded Mine Soils in an Underground Greenhouse" has been examined and approved for acceptance by the Department of Mining Engineering, Montana Tech of The University of Montana, on this 1st day of May, 2018.

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