MOUND MICROSITES: CAN THEY INFLUENCE PLANT SURVIVAL AND GROWTH IN MINE RECLAMATION

By

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ABSTRACT

This study examined arctic lupine (*Lupinus arctica*) and Mackenzie willow (*Salix prolixa*) seedling as well as growing medium responses to the effects of microtopography created by mounding the surface of a waste rock storage facility of a former metal mine in northern British Columbia. In the first two growing seasons of the study, mounding had a significant effect on near surface moisture ($p<0.001$), with moisture in the bottom swales measured to be significantly wetter than the other microtopographical positions, due to the accumulation of water. There were no measured effects on near-surface overburden temperature. The microtopographical treatments significantly affected the concentration of some nutrients, resulting in higher levels in the bottom swales likely due to nutrient leaching and displacement from locations on the mound. Overall plant survival was relatively high, with 5-year survival rates of 81% and 97% respectively for lupine and willow. Both willow and lupine seedlings exhibited highest mortality in bottom swales. Factors that may have contributed to higher mortality rates in the bottom swales include elevated moisture and concentrations of some metals and nutrients as well as reduced root lengths. Lupine cover, biomass and *Rhizobium* nodule formation were also significantly lower on plants occurring in the bottom swales. Similarly, after the first year of growth, willows planted in the bottom swales experienced the lowest cover and shortest root length in comparison to willows planted on the other mound locations. However, after the second year of growth, the highest cover was measured in willow plants occurring in the bottom swales. In this study, the microtopography formed by mounding the waste rock storage facility of a former metal mine facilitated significant differences in physical, chemical, and biological microsite conditions as well as plant survival and growth, at least in the first few years after planting. The created microtopography of mounding may be an efficient tool in influencing overburden characteristics and increasing the diversity of colonizing plant species on a mine reclamation site by providing a variety of sites favorable for seedling development.

Key words: mine reclamation, mounding, microsites, microtopography, native plants

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CHAPTER 1 - INTRODUCTION

Introduction to Reclamation of Metal Mines in BC

The mining industry plays an important economic role in British Columbia (B.C.), Canada, representing billions of dollars in revenues and hosting employment to thousands of British Columbians (NDMF 2016). B.C. is Canada's largest producer of copper and only producer of molybdenum (NDMF 2016). In 2017, there were 19 copper mines in British Columbia (MABC 2017). The operational status varies among the mines, with 5 currently operating, 2 in care and maintenance, 1 in advanced exploration, 10 undergoing permitting or an environmental assessment, and 1 closed (Table 1.1) (MABC 2017).

Table 1.1: Operational status of copper mines in British Columbia in January 2017 (MABC 2017).

Advanced Exploration	**Care and Maintenance**	**Closed**	**Operating**	**Permitting or Environment Assessment**
Foremore	Myra Falls	Kemess South	Copper Mountain	Ajax
	Huckleberry		Mount Milligan	Galore Creek
			Mount Polley	Harper Creek
			New Afton	Kemess Underground
			Red Chris	Kerr-Sulphrets-Mitchell
				Kutcho Creek
				Morrison
				New Prosperity
				Schaft Creek
				Tulsequah Chief

While the extraction of natural resources has reached unprecedented levels, so has the public's appreciation of the principles, values, and structure of mine reclamation. Reclaiming a mine site involves implementing large-scale landscaping and revegetation programs at the ecosystem level, which requires the integration of science and management to effectively achieve reclamation success (Hyman and Leibowitz 2001).

Mine reclamation in BC is guided by provincial and federal regulatory requirements and policy frameworks, including but not limited to the following:

- *Fisheries Act* (1985) and *Metal Mining Effluent Regulations* (MMER) – Imposes requirements for mine closure activities to be implemented in a manner that prevents the introduction of deleterious substances into waters frequented by fish.
- *Mines Act (1996a)* – Section 10 imposes the requirements for environmental protection and reclamation of existing and abandoned mines, including the deposit of a financial security to cover the costs of mine closure and post-closure commitments.
- *Mine Health Safety and Reclamation Code of British Columbia* (2016) – Provides standards for long-term stability of mining disturbances.
- *Environmental Management Act* (2003) – Prescribes requirements and mitigation measures for environmental protection. Regulates contaminated sites, hazardous waste, and spill-reporting regulations.
- *BC Weed Control Act* (1996b) - Imposes a duty on all land occupiers to control designated noxious plants.
- *Species at Risk Act* (2002) - Specifies that invasive plant species that threaten rare wildlife species' habitat must be controlled.

Accessing an ore body involves the removal of subsurface waste rock material that is not economically feasible to process for mineral extraction. During the development of a mine, waste rock material is stored, usually within an existing pit or in a nearby area, forming a waste rock storage facility. Waste rock storage facilities form the surface contours for subsequent reclamation works and end land uses (Toy and Chuse 2005), and can vary in volume, structure and grain size. Long-term stability of mining disturbances is a requirement under the Health Safety and Reclamation Code for Mines in British Columbia (HSRSC) (MEM 2016). Mine features such as storage facilities, impoundments, ditches and watercourses must be reclaimed to resemble adjacent landscapes and ecosystems. The recontouring of waste rock storage facilities is an essential aspect of mine reclamation whereby designs focus on providing stability and aesthetic compatibility with adjacent landscapes (Toy and Chuse 2005). Once the foundation is in place, the focus turns to building an ecosystem from the bottom up, an essential aspect of which is the application of media to support vegetation. In severely disturbed areas lacking soil, such as waste rock storage facilities, an overburden substrate is applied as a substitute for soil. Overburden is waste material overlying the ore deposit that was identified as suitable for use as a vegetation growing medium in reclamation, which may consist of the A, B, and C soil horizons or any combination thereof. In accordance with the *Mine Health Safety and Reclamation Code of British Columbia* (MEM 2016) and in determination through soil surveys, laboratory analyses and field trials, the growing medium applied in reclamation must be protective of the environment, meet all relevant water quality objectives, and must have the capability to support the identified future land use (MEM 2016). During the reclamation process, waste rock storage facilities are coated with an overburden veneer, typically 50-100 cm, and final surfaces prepared for revegetating via mechanical techniques such as disking, harrowing, or mounding (Munshower 1994).

Revegetation Challenges

Reclamation strategies that target returning disturbed sites to some previous historic state may be fundamentally flawed in the context of climate change and relatively newer reclamation philosophies (Hebda 1999). It is generally not possible to recreate the exact same physical conditions with the same species mix as occurred previously. Large-scale disturbances such as mining alter the landscape and impair ecosystem integrity, changing the structure of surficial materials and drainage channel systems such that even if the ecological blueprint of the site’s historic state did exist, replication would not be practically achievable (Hebda 1999). Therefore, it is important to understand the potential limitations and challenges of the site that is being reclaimed to achieve some level of reclamation success.

One such challenge is related to dispersal limitations. The process of propagule dispersion has important consequences in the context of mine reclamation, as the overburden growing medium on a waste rock storage facility generally lacks a seed bank. For a plant to colonize a waste rock storage facility, it must travel to the site through a variety of mechanisms such aswind, gravity, floatation, animal movement, and ballistically (Kraft and Ackerly 2014). Most seeds disperse only short distances and do not directly target sites with optimal germination conditions (Kraft and Ackerly 2014). On a waste rock storage facility with less than optimal ecological conditions and relatively far dispersal distance, few seeds may arrive from adjacent seed sources and germinate only infrequently. Therefore, waste rock storage facilities tend to be dispersal limited, resulting in relatively slow ingress of native species (Eriksson and Ehrlen 1992).

Another revegetation challenge is that the alteration of soil properties caused by the displacement, storage and replacement of surficial materials may limit species establishment or survival in particular habitat conditions (Kraft and Ackerly 2014). Details on the alteration of soil properties are presented below.

Overburden Properties and Impacts on Plant Establishment

The majority of surficial disturbance occurs during the mine's construction phase as a result of surface clearing, and removal of stumps along the proposed footprint of the mine's infrastructure. It is at this stage that topsoil and overburden resources are salvaged and stored for future use in reclamation. Storing soil resources for any length of time results in changes to soil temperature, water storage potential, bulk density, electrical conductivity, as well as changes to the level and availability of nutrients, oxygen, and carbon (McQueen and Ross 1982, Abdul-Kareem and McRae 1984, Kundu and Ghose 1994, Ghose 2002, Ghose 2004, Mackenzie 2013). From the time the soil is stripped, its ecological functionality is altered, resulting from changes to soil physical, chemical, or biological properties (Ghose 2002). Key ecological functions of soil that may be disrupted include, providing a medium for vegetation growth, influencing plant species composition, providing wildlife habitat, nutrients and water storage potential, water filtration capabilities, and control of sediment into waterbodies. In addition, soil quality may be affected by soil compaction, contamination, and erosion. Nonetheless, when surficial materials are stripped during mine construction and development, they are stockpiled for reclamation purposes with the expectation that, when re-applied, they will eventually regain the ecological functionality of soil.

The overburden placed on waste rock storage facilities serving as a vegetation growing medium in reclamation is expected to provide the resources to establish vegetation, including nutrients, moisture, and pore space for oxygen, root expansion and anchorage. The availability of these resources must be examined to understand how they will influence plant survival and growth and the developmental change in biotic expression over time. Furthermore, characterizing the chemical, physical, and biological properties of overburden is critical in understanding the effectiveness and limitations of the habitat conditions created during the reclamation process (Sheoran et al 2010, Maharana and Patel 2013). Overburden properties measured over time can be used as indicators for assessing the site's productivity and help to guide reclamation efforts (Pasayat and Patel 2015). Overburden properties that may affect plant establishment are detailed further below.

Chemical Properties

The pH of overburden is an indicator of growing medium quality. For most vegetation, the optimal range of pH in a growing medium is generally 6.6-7.3, which is considered neutral (Munshower 1994). However, it is common in nature to see pH values slightly acidic and slightly alkaline (Munshower 1994). It has been reported that when overburden pH occurs below 5.5, legume and forage growth can be inhibited due to an induced toxicity to metals that become more bioavailable at lower pH (Sheoran et al 2010).

Electrical conductivity (EC) is a measure of overburden salinity, which is the amount of soluble salt in the growing medium. Generally, in an agricultural context, growing mediums with an EC greater than 4 dS/m are classified as saline (Munshower 1994). In a mine reclamation setting, overburden with EC less than 4 dS/m may affect the establishment of plants that are sensitive to salt (Munshower 1994).

Elements required in large quantities for plant growth and development, referred to as macronutrients, include nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur. Overburden tends to be deficient in macronutrients such as nitrogen, phosphorus, and potassium (Sheoran et al. 2008). Throughout a mine's life, nitrogen content in overburden stockpiles is subject to volatilization, fixation by clays, conversion back to nitrate or free nitrogen, and leaching (Munshower 1994). By the time overburden is redistributed onto a waste rock storage facility, its nitrate ion content may already be depleted. Overburden with depleted nitrogen may not affect seed germination, but may have direct negative implications on seedling growth (McGinnies and Croft 1986), resulting in small pale green plants. Plants with phosphorus deficiency may display reduced growth, discoloration of foliage and stems (reddish-purple), and lifeless leaf tips (Munshower 1994).

Cation exchange capacity (CEC) is a measure of fertility, referring to the concentration of cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, H^{+}) that can be adsorbed by a growing medium such as overburden. Cations are attracted to negatively charged overburden particles or colloids. These are exchange sites on which the cations held can exchange places with cations in the soil solution, making them available for plant uptake and subject to leaching. Ions displaced from the growing medium faster than they can be supplied by weathering or decomposition may result in deficiencies that may affect plant growth (Munshower 1994).

The concentration of sodium ions measured in overburden supplements its alkalinity level. Overburden characterized with elevated sodium ion levels, compared to calcium and magnesium ion levels, may present a risk to plant's ability to absorb water, thereby inhibiting plant growth (Munshower 1994).

Organic matter in a forestry or agriculture context consists of the percent of humus measured in the soil. However, organic matter in a reclamation setting includes any amendments applied to the site, such as straw, mulches, biosolids, wood chips, etc. Organic matter less than 2.0% is considered to be very low (Munshower 1994). Total organic carbon is a measure of the carbon contained within overburden organic matter. It has been reported that a level of organic carbon greater than 0.75% is adequate to support plant growth (Ghose et al. 2010).

Physical Properties

Coarse fragments are those greater than 2 mm. Overburden is generally high in coarse fragment with larger pores with limited water holding capacity, which is restrictive to plant growth. Overburden with coarse fragment greater than 50% is considered poor quality (Hu et al. 1992).

Texture refers to the relative amount of sand, silt, and clay in a soil sample, as determined from a laboratory particle-size distribution. Many overburden properties are influenced by its texture, such as aeration, water infiltration and storage capacity, cation exchange capacity and erosion potential (Munshower 1994; Leavitt et al. 2000). These properties play important roles in a plant's ability to extract water and nutrients. For example, the abrupt change in texture between overburden and waste rock material may affect root development (Eapen et al. 2005) by restricting water and nutrient movement at the interface between the two layers (Li and Liu 2011). Furthermore, the overburden veneer applied to waste rock storage facilities, which varies by site and prescription, may affect root development by limiting the depth at which roots extend and may foster more lateral root growth (Jung et al. 2014).

Overburden moisture content in a sloped metal mine waste rock storage facility is a fluctuating parameter that can be influenced by the dump's surficial microtopography and texture of materials present (Sheoran et al 2010). Differences in moisture conditions in soil have been shown to affect plant community composition (Curran and MacNaeidhe 1985, Price et al. 1998, Lachance and Lavoie 2004, Bubier et al. 2006) and total cover (Bubier et al. 2006) on disturbed sites.

Plant growth is also influenced by the temperature of its growing medium (Willis and Power 1975). Elevated soil temperatures increase water evaporation such that water availability to plants may be decreased. Furthermore, some plant functional groups, which are sets of plants with similar ecological functions and resource requirements, are more sensitive to variations in soil temporal properties. For example, it has been shown that the optimum soil temperature for highest growth of nitrogen-fixing species is 25°C (Redell et al. 1985).

Biological Properties

Overburden that has been stockpiled for any length of time experiences a disruption in soil layers and biological expression. Overburden's biological legacy, or the biological material remaining (Franklin 1990), after storage and replacement is often devoid of vegetation and a seedbank and its ability to provide wildlife habitat is altered. Furthermore, the functionality of overburden's microbial, bacterial, and fungal communities is also diminished (Sheoran et al. 2010). Combined, these changes result in an overall modification in biotic expression compared to that of native soil. Recharging overburden's microbes is beneficial to facilitate the recovery of ecological processes and may be achieved by planting vegetation that perform as hosts (Sheoran et al. 2010). It has been shown that interactions between plants and microbial organisms can affect community development (Kraft and Ackerly 2014). For example, symbiotic relationships formed with other organisms can enable some plant species to establish in areas where they would otherwise not be able (Kraft and Ackerly 2014). *Rhizobia*, bacteria belonging to the family Rhizobiaceae, form a symbiotic relationship with legume plants. These bacteria serve plants by converting N^2 into NH_4^+; that is a form of nitrogen that plants cannot use into a form that they can. Nitrogen fixing legumes, particularly lupine plants, have been shown to facilitate the growth of other species on disturbed sites (Del Moral and Wood 1993). This means that on disturbed sites with nutrient deficient soils, lupine and *Rhizobia* together promote soil development and facilitate plant growth, with the ability to fix nitrogen, and thereby increase the amount of nitrogen available to other plants. Therefore, nitrogen-fixing plant species, such as lupine, are often solicited for use in the reclamation of severely disturbed sites with nitrogen-deficient soils.

Microsites

Microsites, in a vegetation context, are sites with unique features that serve to allow seedlings to emerge successfully from the soil (Eriksson and Ehrlen 1992, Elmarsdottir et al. 2003). Microsites offer small-scale pockets of unique environmental conditions that may vary by physical, chemical, or biological properties, such as soil nutrient availability, temperature, moisture, texture, vegetation cover, available sunlight, and soil biotic organisms (Tsuyuzaki et al. 1997, Elmarsdottir et al. 2003). Information on microsite conditions and their effects on seedling growth and survival is important in order to facilitate ecosystem recovery in reclamation (Elmarsdottir et al. 2003).

Ecosystem recovery proceeds slowly on severely disturbed sites with poor soil quality (Bradshaw 1983, Tsuyuzaki et al. 1997), such as on the overburden-covered surface of the waste rock storage facility of a former metal mine. Therefore, in the context of reclamation management, it is important to create environmental conditions that are conducive for vegetation to establish in a reasonable timeframe (Elmarsdottir et al. 2003). Conditions favourable for native seedling emergence and survival on a disturbed site may be achieved by creating microtopographic heterogeneity (Galatowitsch 2008, Biederman and Whisenant 2011). It has been shown that fine-scale microtopographic heterogeneity influences successional processes such as seedling growth and survivability on a severely disturbed site by forming mounds as a final surface preparation technique (Biederman and Whisenant 2011).

Mounds and swales are comprised of concave and convex structures applied across a disturbed site, forming microsites that may differ by aspect, growing medium depth, nutrient concentrations (El-Bana et al. 2003; Bruland and Richardson 2005), and moisture (Bledsoe and Shear 2000; Löf et al. 2006). The mounding technique is often used in a variety of environmental settings, including forests (Cornett et al. 1997; Yates et al. 2000), wetlands (Fraser and Kindscher 2001; Peach and Zedler 2006), tidal marshes (Weinstein et al. 2001), grasslands (Hough-Snee et al. 2011), and landfills (Ewing 2002) as a method to introduce microtopographic variation in soil surfaces to prepare for revegetation. Fluctuations in microsite conditions within the concave-convex features appear to facilitate differentiation in plant species composition (Schor and Gray 2007; Schladweiler et al. 2005). Mounds and swales, therefore may contribute to plant establishment and growth in mine reclamation settings (Lane and BassiriRad 2005; Biederman and Whisenant 2011; Gilland and McCarthy 2013), but the effects of mounding on mining overburden physical and chemical properties and how these relate to vegetation establishment have rarely been studied.

Revegetation

Reclamation managers facilitate the introduction of living organisms that are expected to perform ecosystem recovery. This novel ecosystem approach has been recently defined as "a system of abiotic, biotic, and social components (and their interactions) that by virtue of human influence, differs from those that prevailed historically, having a tendency to self-organize and manifest novel qualities without intensive human management" (Hobbs et al. 2013).

The revegetation philosophy in a mining context in British Columbia is to develop a plant community that is self-sustaining, and conducive to the site's end land use (HSRC 2016), which may include future uses such as range land, wildlife habitat, and forestry, among others. For a plant community to be self-sustaining on a severely disturbed site, species planted must have high reproduction performance, which requires a tolerance for extreme abiotic conditions in the germination, establishment, and adult reproductive phases (Kraft and Ackerly 2014). Tolerance levels for extreme abiotic conditions, such as elevated soil metal concentrations and deficient nutrient levels, vary by species (Kraft and Ackerly 2014). Therefore, in considering the species to develop a self-sustaining plant community on a waste rock storage facility, it is just as important to consider the extreme abiotic conditions present. The species selected for use in reclamation should reflect the site's future land use and apply plant material (i.e. seeds, cuttings, etc.) adapted to the site conditions. For Kemess Mine, located in northern BC, two species considered for large-scale application in reclamation include Arctic Lupine (*Lupinus arcticus*) and Mackenzie Willow (*Salix prolixa*). Their life histories and suitability for use in reclamation are detailed below.

Arctic Lupine

Arctic lupine, *Lupinus arcticus*, (Fabaceae), is a perennial herb occurring in British Columbia north of 55 N (Douglas et al. 1999). In areas that it inhabits, it is regarded as an early colonizing species, often inhabiting exposed mineral soil and early-seral conditions (Klinka et al. 1998). Its intolerance to shade and ability to fix nitrogen (Klinka et al. 1998) make this species an ideal candidate for application in reclamation projects where soil is often nitrogen-deficient with little shade availability. These terrestrial plants produce seeds that are easily collected from dehiscing pods for commercial propagation. Although the germination success of various lupine species seeds in restoration projects varies (6-50% after one year) (Bowles et al. 1997, Pavlovic and Grundel 2008), and just 23% of transplanted germinants survived after one year (Bowles et al. 1997), there have been few studies examining the effectiveness of transplanting nursery-sown lupine container seedlings, particularly in the context of reclaiming the waste rock storage facility of a former metal mine.

Mackenzie Willow

There are over 300 species of *Salix*, a perennial shrub distributed predominantly in the Northern Hemisphere (Kuzovkina and Volk 2009). Mackenzie Willow, *Salix prolixa* (Salicaceae), is a shrub distributed throughout British Columbia. It was first identified growing along the Mackenzie River and was named after the explorer Alexander Mackenzie. Mackenzie Willow, like most willow species, is considered apt as a pioneering species (Kuzovkina and Volk 2009) growing well on disturbed sites. It is an important source of food, building material and nesting location for wildlife and has been commonly used in the restoration of riparian areas (Crowder 2003). However, little work has been recorded on the use of Mackenzie willow in the context of mine reclamation.

Thesis Research Objectives

Creating ecologically habitable conditions on the waste rock storage facility of a former copper mine is a complex process, and developing strategies for measuring and communicating ecological responses to the conditions created is a difficult but essential task to effectively assess the success of any large-scale reclamation program (Dale and Beyeler 2001, Schiller et al. 2001, Lausch and Herzog 2002, Niemi and McDonald 2004, Ruiz-Jaen and Aide 2005). Performing biophysical manipulations, such as surficial mounding, to the overburden-covered surface of the waste rock storage facility of a former metal mine with the focus of assessing the performance of select plant species transplanted to the created microsites has rarely been studied (Elmarsdottir et al. 2003). The objective of this study, presented in Chapter 2, is to examine how substrate characteristics occurring after final surface preparation (mounding) of the waste rock storage facility of a former metal mine differ among topographical positions and provide insight into how these characteristics influence the survival and development of arctic lupine and Mackenzie willow. In Chapter 3 I examine the results to assess how they may contribute to adaptively managing effective reclamation undertakings in metal mines in British Columbia.

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CHAPTER 2 - RELATING THE SURVIVAL AND GROWTH OF PLANTED WILLOW AND LUPINE SEEDLINGS TO MICROSITE CONDITIONS CREATED BY MOUNDING THE WASTE ROCK STORAGE FACILITY OF A FORMER METAL MINE

Introduction

The economic extraction of an ore deposit is accompanied by the extensive alteration of land forms and the alteration or loss of ecosystem integrity and function within the mining project's footprint. When the legacy of a mine site includes a severely disturbed landscape that cannot rely solely on successional processes to restore it to ecologically habitable conditions (Rietkerk et al. 1997), sites require direct intervention by land managers to enhance terrain stability and functional productivity, the practice of which is referred to as reclamation. In British Columbia, mine reclamation is mandated by a framework of regulations and guidelines (BC MEM 2016) and is incorporated into mine planning. Mine features must be reclaimed to ensure long-term stability and resemble adjacent landscapes and ecosystems, using species that are conducive to a predetermined future land use (BC MEM 2016).

Open pit mining involves the permanent relocation of rock material that is not economically feasible to be processed, referred to as waste rock. Mine waste rock storage facilities comprise the foundations for subsequent reclamation undertakings and form the surfaces of the transitioned landscape (Toy and Chuse 2005). Common challenges to reclaiming waste rock storage facilities include instability of unconsolidated spoil material, substrate compaction due to heavy equipment usage and surficial erosion (Gilland and McCarthy 2013). Waste rock storage facilities with topographic designs consisting of long uniform slopes with convex or straight profiles, such as those typically formed in surface mine areas (Toy and Chuse 2005), contribute to an unbalanced conveyance of surface runoff prone to severe scouring of sediment (Hancock et al. 2003; Sanz et al. 2008). In addition, waste rock substrate tends to be very coarse with biological deficiencies, and the textural interface between the waste rock material and the growing medium cover can affect the distribution of water and nutrients (Jung et al. 2014), hindering vegetative establishment (Zhang et al. 2015). Reclamation projects often fall short in restoring biological diversity by introducing a relatively small number of species expected to grow there, which tends to be a fraction of the species richness found in adjacent undisturbed sites (Galatowitsch 2008). With the high costs associated with the application of native seed and seedlings for reclamation, efforts should be made such that site conditions are ecologically habitable for native seedling development and growth (Galatowitsch 2008) and landforms conducive to a balanced hydrological system (Ghose 2004).

Mounds and swales are pronounced elements of microtopographic variation in soil surface elevation, applied in different environmental settings, including forests (Cornett et al. 1997; Yates et al. 2000), wetlands (Fraser and Kindscher 2001; Peach and Zedler 2006), tidal marshes (Weinstein et al. 2001), grasslands (Hough-Snee et al. 2011), and landfills (Ewing 2002) as a component of final surface preparation to enhance revegetation success. Mounds and swales are comprised of concave and convex structures applied across a disturbed site, creating microtopographical features that reduce erosion potential by decreasing the tributary drainage area allotted to each swale and regulating general slope runoff (Schor and Gray 2007), mitigating the unbalanced water distribution associated with uniform slopes (Bugosh 2004; Martin-Duque et al. 2010). The fine-scale microtopography created by mounds and swales differs from that of a smooth, uniform landscaping approach in that it increases the overall surface area of the site and provides heterogeneity by forming microsites that differ by aspect, growing medium depth, nutrient concentrations (El-Bana et al. 2003; Bruland and Richardson 2005), and moisture (Bledsoe and Shear 2000; Löf et al. 2006). Conditions favourable for native seedling emergence and survival on a disturbed site may be achieved by creating microtopographic heterogeneity (Galatowitsch 2008, Biederman 2010). The application of mounds and swales offers opportunities for differentiation of plant species composition to occur at the microtopographic level due to the fluctuations in habitat conditions within the concave-convex slope elements (Schor and Gray 2007; Schladweiler et al. 2005). Mounds and swales, therefore may contribute to plant establishment and growth in mine reclamation settings (Lane and BassiriRad 2005; Biederman and Whisenant 2011; Gilland and McCarthy 2013).

While a number of recent studies have been conducted on plant and soil responses to mounding in a forestry or grassland settings (Cornett et al. 1997; Yates et al. 2000, Hough-Snee et al. 2011), little information is currently available on the effect of mounding on overburden and plant survival and growth in a mining context. The extent to which mounds and swales may contribute to plant establishment and growth in the context of mine reclamation depends on the characteristics of the growing medium (Biederman and Whisenant 2011). Overburden texture affects plant growth resulting through changes in overburden aeration, water infiltration and storage capacity, cation exchange capacity and erosion potential (Munshower 1994; Leavitt et al. 2000). Fine-textured overburden sediments may accumulate in the swale of a mound contributing to plant growth by facilitating increased root contact with soil particles (Leavitt et al. 2000). Gradients of nutrient availability may develop in the mounds and swales, resulting from leaching of nutrients (Leavitt et al. 2000), with higher availability in the bottom swale and less at the top mound. Similarly, greater overburden moisture is likely to occur in the bottom swales due to the accumulation of snow and runoff water in the bottom swales of the mounds.

Seedling establishment and plant community development may be limited on sites with low productivity and a limited seed source (Eskelinen and Virtanen 2005; Galatowitsch 2008; Pywell et al. 2002; Martin and Wilsey 2006; Leavitt et al. 2000). The selection of suitable plant species for prescriptive applications at specified locations is critical in successful reclamation programs (Licht and Isebrands 2003; Kuzovkina and Volk 2009). The application of fast-growing species, such as willow, and nitrogen-fixing species such as lupine, have been suggested as solutions for the revegetation of disturbed sites such as waste rock storage facilities in some geographic locations.

There are over 300 species of *Salix*, a perennial shrub distributed throughout the world, predominantly located in the Northern Hemisphere (Kuzovkina and Volk 2009). The ecological attributes of *Salix* species have been the subject of an array of research pertinent to the application of willows for land reclamation, phytoremediation, bioengineering, and agroforestry (Kuzovkina and Volk 2009). Many willow species are classified as early colonizing species (Argus 1986; Skvortsov 1999), which indicates they establish on disturbed sites such as mine waste dumps and can tolerate varying degrees of mesic and hydric conditions, shallow and compacted growing mediums, limited nutrient availability, and elevated metal concentrations (Logan 1992; Hightshoe 1998; Kuzovkina and Volk 2009). In addition, willow species grow rapidly (Dickmann 2006) with high biomass (Weih 2004) on disturbed sites and can tolerate a high density of planting (Keoleian and Volk 2005); however they are intolerant to shade ((Kuzovkina and Volk 2009). Willow shrubs also have a reliable coppicing ability (Kuzovkina and Volk 2009). These characteristics suggest that willows might be suitable for a variety of reclamation applications, with a high survivability and growth rate expected in different settings. However, little is known about how willow plants will respond to created microtopography on a waste rock storage facility of a metal mine.

Lupinus arcticus is a nitrogen-fixing legume native to British Columbia that has colonizing capabilities making it applicable in restoration projects. After disturbance, lupine is one of the first native species to recolonize the site (Del Moral and Wood 1993). A study by Del Moral and Wood (1993) found that lupine plants also have the ability to facilitate the colonization of other species. The study noted a flux of other species that colonized the site after a pre-existing lupine plant had died (Del Moral and Wood 1993). This is an indication that on disturbed sites with nutrient deficient soils, lupine promotes soil development and facilitates plant growth, with its ability to fix nitrogen, and thereby increasing the amount of nitrogen available to other plants. According to Hendrickson and Burgess (1989), *Lupinus arcticus* can fix nitrogen at a rate of 2 kg/acre/year in a clear-cut area. In addition to building soil, lupine's deep roots control sediment transport and erosion stabilizing the soil. This is a key component in mine reclamation programs, including the Quintette Mine in northern BC (Smyth 1995). Furthermore, lupine seeds are relatively easy to collect for use in reclamation projects. However, little is known on how lupine plants will respond to created microtopography on a waste rock storage facility of a metal mine.

This study examines plant and overburden responses to created microtopography on the surface of a waste rock storage facility of a former gold and copper mine located in Northern British Columbia. Specifically I correlate differences in physical properties of the overburden surface among microtopographic positions with lupine and willow survival and growth at different microtopographic positions on a mounded overburden surface of a gold and copper mine waste rock storage facility.

Objectives

The objectives of the research study include determining whether differences in microtopography affect overburden physical and chemical properties and whether these differences are reflected in native plant survival and growth. Specific objectives of the study are to:

- Quantify effects of microtopography on near surface overburden physical properties, including temperature and moisture.
- Quantify effects of microtopography on near surface overburden nutrient availability and texture.
- Quantify effects of microtopography on lupine and willow survival and growth.

Hypotheses

It is expected that overburden physical properties will differ among the created microtopographic positions. It is also expected that plant (lupine and willow) survival and growth will differ at the different microtopographic positions on the contoured overburden surface of the waste rock storage facility.

Methods

Site Description

Kemess Mine Site

Kemess South Mine (Kemess) is an open-pit gold and copper mine located in north-central British Columbia. The majority of surficial disturbance occurred during the mine's construction phase as a result of surface clearing, grubbing and stripping along the proposed footprint of the mine's infrastructure. The initial ground disturbance associated with the construction of the mine began in 1996 and was completed by 1998 when the economic extraction of the porphyry deposit commenced (AuRico 2016). Kemess Mine ceased operating in 2011.

The Kemess Mine is located 8 km east of Thutade Lake, in the northern Omineca Mountains of north central British Columbia (Figure 2.1). The mine is approximately 430 km northwest of Prince George. The coordinates of the mine site are latitude

57°00”N, longitude 126°45’W, and the mine development area straddles the National Topographic System 94D / 15 and 94 E / 2 map sheets. The remote site is accessed seasonally by the Omineca Resource Access Road (ORAR) and by air, with passengers being flown from Smithers and Prince George. The closest community to the mine is Tsay Keh Dene.

Kemess Mine is located on the western margin of the Swannell Ranges of the Omineca Mountains, within the Mackenzie Forest District (AuRico 2016). The mine site is situated within the Kemess Creek drainage basin and Waste Rock Creek catchment areas. Both creeks drain into Attichika Creek, which is a tributary to Thutade Lake. Thutade Lake is the headwater to the Finlay River, which drains to the Peace River and then joins the Slave River, and ultimately empties in the Arctic Ocean via the Mackenzie River (AuRico 2016).

The area within the Kemess Mine development boundary is characterized by two biogeoclimatic subzones: the Spruce-Willow-Birch moist cool (SWBmk) and the Spruce-Willow-Birch moist cool scrub (SWBmks) (Banner et al. 1993; Delong 2004 and Mackenzie 2012). These zones are characterized by warm, dry summers and cold, wet winters. Annual temperatures generally range from -35°C to 25°C (Beaudry 2016). Annual precipitation is approximately 700 mm, 550 mm of which is snow water equivalents. January is typically the coldest month and July is the warmest month (Beaudry 2016).

Kemess South Project Location

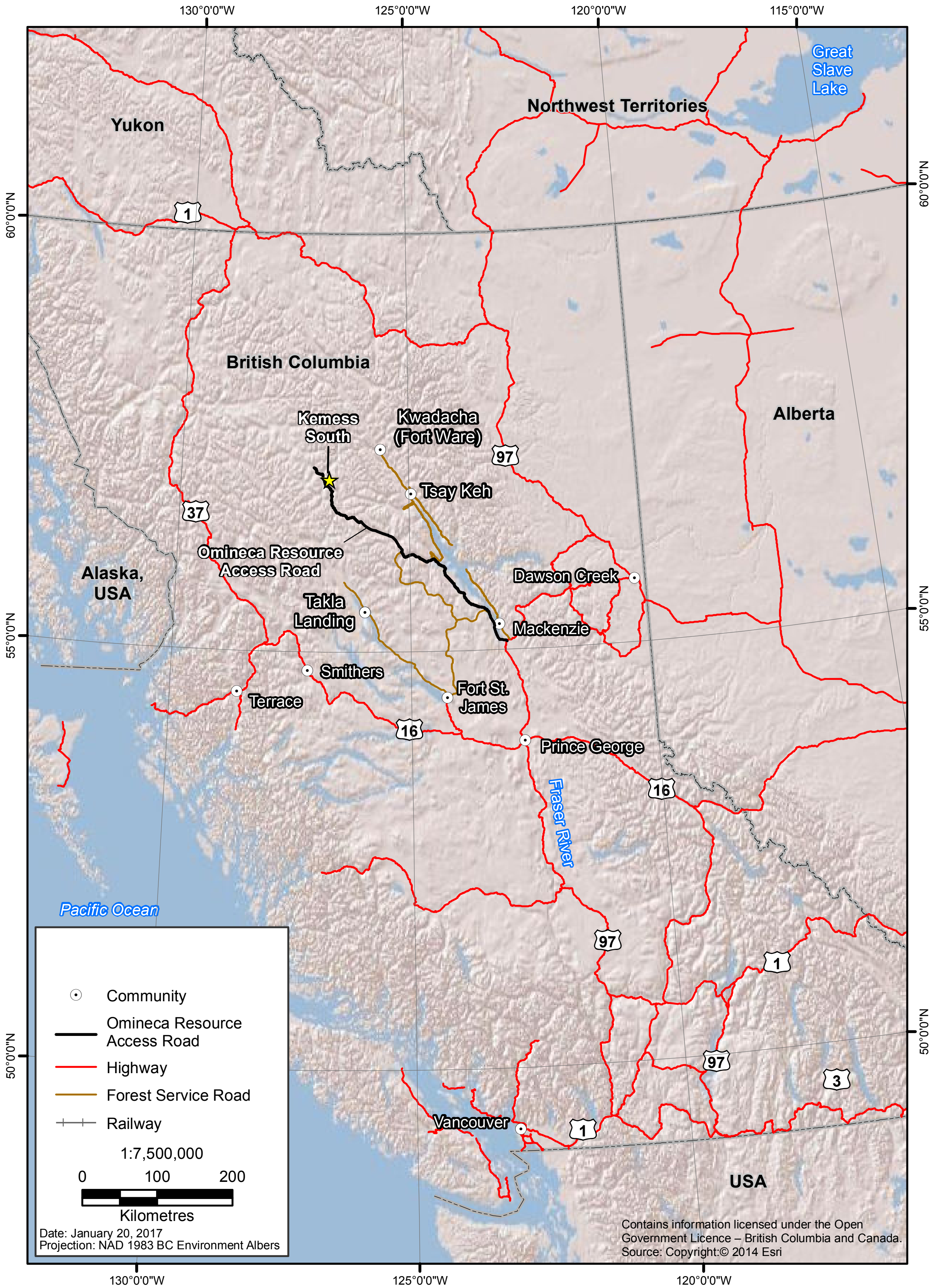

Figure 2.1: The study site is located 8 km east of Thutade Lake, in the northern Omineca Mountains of north central British Columbia at AuRico Metal’s Kemess South Mine.

The SWBmk subzone is generally situated between 1200 m and 1500 m elevations and is dominated by white spruce (*Picea glauca*), sub-alpine fir (*Abies lasiocarpa*), scrub birch (*Betula glandulosa*) and various willow species (*Salix* sp.). The SWBmks generally occupies subalpine elevations ranging from 1200 m to 1700 m. It is dominated primarily by shrubs such as, scrub birch (*Betula glandulosa*), various willow species (*Salix* sp), subalpine fir krummholz and white mountain-heather (*Cassiopia mertensiana*) heaths.

Waste Rock Storage Facility and Surficial Material

Waste rock not economically feasible to be processed through the mill was removed from the open pit to access ore and relocated to an area referred to as the Waste rock storage facility for permanent storage. The waste rock storage facility at Kemess Mine consists of 169 Mt of waste material, consisting of Toodoggone Tuffs, Leach Cap Waste, and Asitka sediments, ranging in size from clay to boulders; the waste rock substrate was covered with a layer of overburden (AuRico 2016). The waste rock materials are classified as non-acid generating (NAG) and are characterized as follows (AuRico 2016):

- Toodoggone Tuffs – comprised primarily of polylithic lapilli tuffs with sericite altered lithic fragments;
- Leach Cap Waste – quartz monzodiorite with sericite and hematite alterations;
- Asitka – thin chert layer with intercalated clay/siltstone layers; intermediate to mafic and felsic intrusive rocks with some indication of carbonate and chloritic alterations;
- Overburden – non-lithified surficial material containing ablation till, includes mineral and organic materials, with soil from A and B horizons, plus proportionately more material from the C-horizon.

Waste rock substrate was placed in the waste rock storage facility in a series of three ascending lifts using a method called the end-dump method, where rock is poured from a haulage truck onto the waste rock storage facility slope face. After initial placement of materials, the slopes were recontoured to a final slope angle of 27° and in 2009 a layer of overburden was applied to the surface to achieve a depth of 1m. In the same year, surficial mounds were subsequently formed to diversify microtopography and to increase environmental heterogeneity. This application was also intended to decrease compaction and reduce erosion potential. The mounds were created by excavating one bucket of material to form a swale and placing the contents of the bucket adjacent the newly-formed swale. All mounds were on average 1.5 m long, 1.5 m wide and achieving an overburden depth of 1.5 m at the top mound and 0.5 m in the bottom swales.

Study Site

The study was conducted on the northwest corner of Kemess Mine's Main NAG waste rock storage facility, specifically on one southwest aspect slope and one northwest aspect slope. The location of the general study area is presented in Figure 2.2.

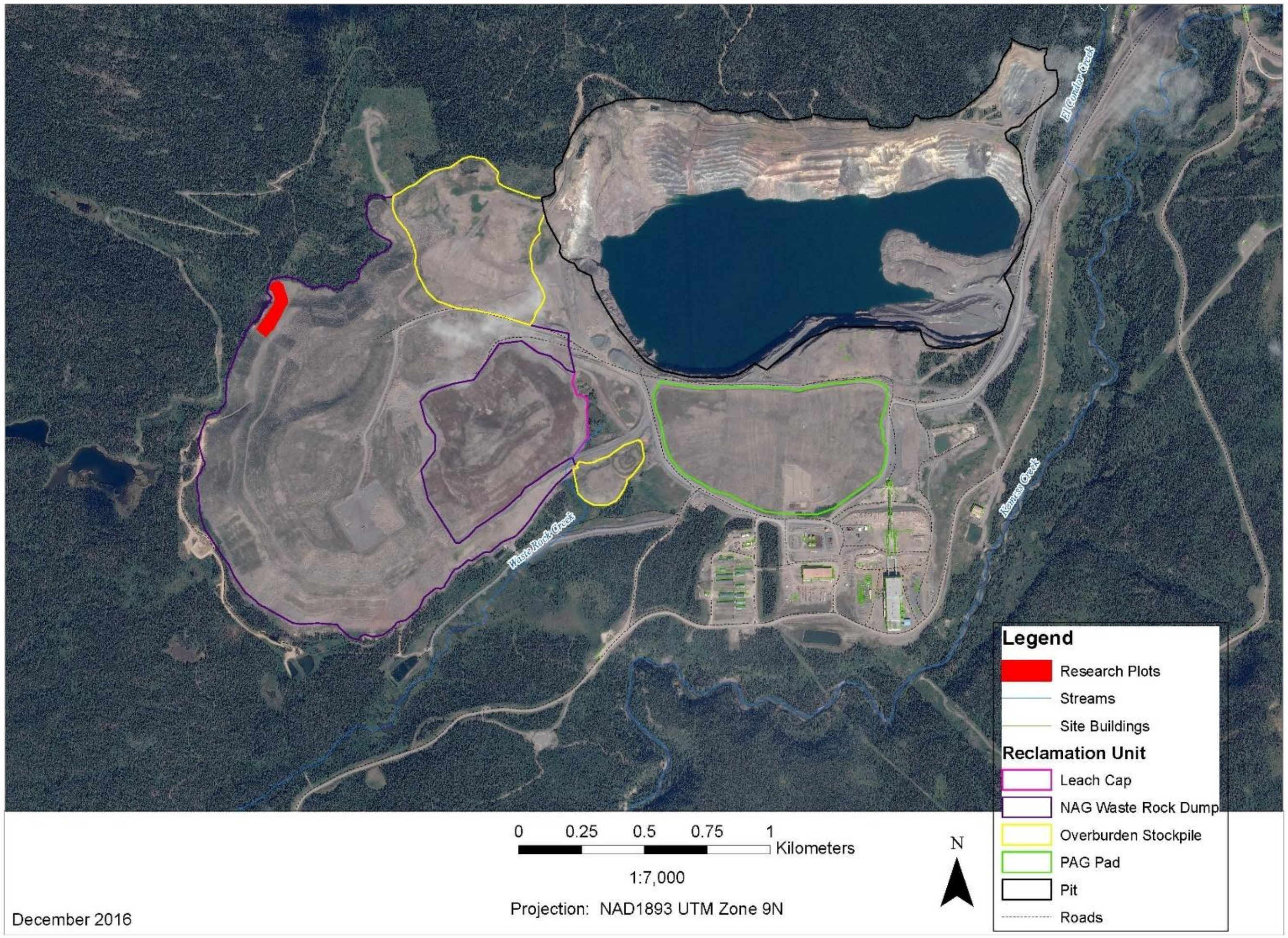

Figure 2.2: The study site is located on the northwest corner of Kemess Mine's Waste rock storage facility, indicated by the red polygon on the figure.

Experimental Design

To test the effect of aspect and microtopography on willow and lupine establishment and growth, I used a randomized complete block design with 4 treatments consisting of mound topographical positions (top mound (T), bottom swale (B), slope uphill (SU), and slope downhill (SD)), that was blocked by two slope aspects (on northwest and southwest slopes), with the SU and SD positions differing by aspect (Figures 2.3 and 2.4). All four treatments were replicated ten times on the northwest slope and five times on the southwest slope for both species (*Lupinus arcticus* and *Salix prolixa)* independently. At each mound one species was planted in only one of the four locations. In total, 120 different mounds were planted to create 15 replicates per treatment per species.

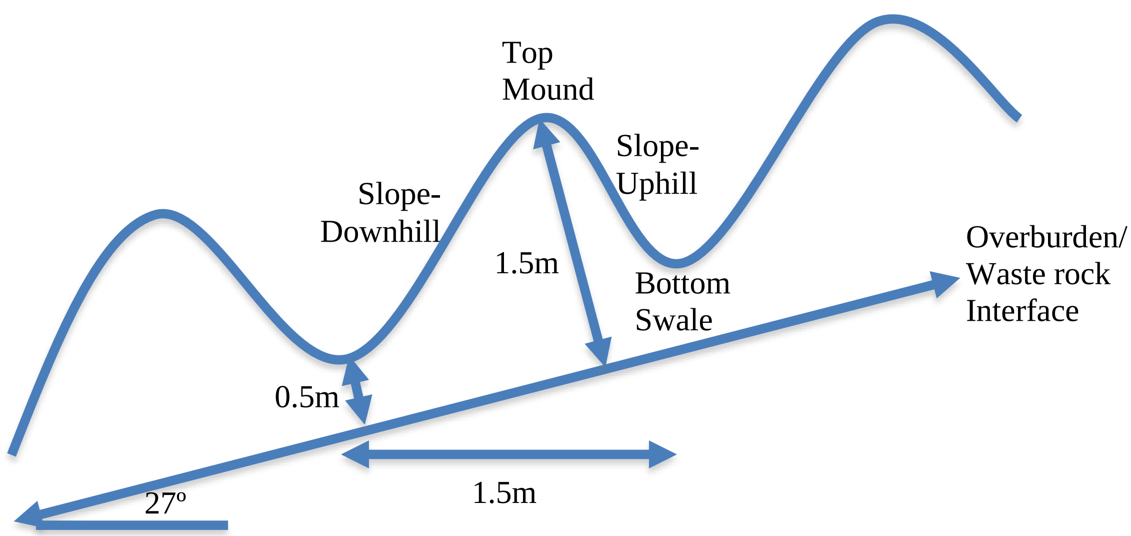

Figure 2.3: Illustrated representation of the microtopographic features (treatments) established at the site.

Figure 2.4: Study located on mounded waste rock storage facility at AuRico Metals' Kemess Mine site.

Sampling Methods

Plant Taxonomy, Collection, Propagation and Establishment

Species in this study were selected based on the composition of the early colonizing communities in nearby disturbed sites. In 2009, plants were identified in the field to species level according to the guide Plants of Northern British Columbia (MacKinnon et al. 1992) and later confirmed with Illustrated Flora of British Columbia (Douglas et al. 2000). The two species used in the study were identified as *Lupinus arcticus* (Arctic Lupine) and *Salix prolixa* (MacKenzie willow). For the purposes of this study, lupine was propagated by seed and willow was propagated vegetatively.

Lupine seeds were collected in July 2009, following procedures outlined in Kemess' Lupine Seed Evaluation (Evans 2009) (Appendix A). Lupine pods were collected in burlap sacs and later screened to separate the seed, removing debris and unviable seeds. Willow cuttings were harvested late fall 2009 when the plants were dormant. Cuttings were harvested along the Omineca Resource Access Road (ORAR) and cut to length at a commercial nursery. All seeds and cuttings were sent to Woodmere Nursery in Telkwa, British Columbia for commercial propagation and growth. The nursery in Telkwa follows standard nursery procedures in their propagation practices. For lupine seeds, all seeds underwent cold-moist stratification for 30 days. The seeds were then soaked in water for 24 hours and subsequently placed on a growing medium. After germinating, the sprout was transplanted to a 410A-sized cavity filled with potting soil for root development and growth. The willow cuttings were dipped in rooting hormone number 3 and then placed in 412A-sized cavities filled with potting soil for root establishment and growth.

Willow and lupine plugs, ready to be planted, were shipped to the site from Telkwa in a refrigerated truck, which arrived to site June 30, 2010, when plants were approximately 6 months old. Transplants were randomly assigned to four different topographical positions in the study area on the waste rock storage facility: bottom swale (n = 15), slope-downhill (n = 15), slope-uphill (n =15) and top mound (n = 15). Three plugs of the same species were planted in each plot (topographical location) spaced 0.5 m apart, to ensure survivability so that statistical analyses could be conducted. This method was repeated for both willow and lupine.

Overburden Data Collection

Near surface overburden moisture and overburden temperature were measured concurrently using a Stevens Hydra Probe Soil Sensor, calibrated to overburden from the sample site. To reduce variability from weather conditions, the measurements occurred between 11:30 am and 1:30 pm on sample days. Moisture and temperature readings were taken in the top 5.7 cm of overburden, adjacent to a plant at all topographic locations in each experimental unit, alternating between willow and lupine plots on the sample days. A reading was taken in each willow or lupine plot on the northwest aspect plots and/or the southwest aspect plots. Overburden moisture and temperature readings were taken following procedures outlined in the Comprehensive Stevens Hydra Probe Users Manual (2007). Probes were wiped clean between measurements to avoid biasing the subsequent readings.

Temperature was recorded in degrees Celsius. The water content in the top 5.7 cm of overburden was recorded as a water fraction by volume (wfv), which is a dimensionless ratio of two volumes (i.e. 0.10 wfv means that a one liter sample contains 100 ml of water). The dimensionless ratio can be reported as a percentage if multiplied by 100.

Means for overburden moisture and temperature were calculated for the 2010 and 2011 growing seasons from the data collected in July, August and September 2010, for a total of 16 sample days and in June and August 2011, for a total of 2 samples days.

Overburden was sampled in 2009, 2010 and 2015. In 2009, overburden stockpiles were sampled prior to placement on the waste rock storage facility. Samples were taken at the surface and 1 m depths. In 2010 and 2015, overburden samples were taken in the top 15 cm of the substrate. Overburden was sampled adjacent the plants in each plot and combined to form a thoroughly homogenized composite sample from each topographic position. Each treatment was sampled four times (twice in each block), for a total of 16 samples. Overburden samples were collected using a core sampler (core diameter 7.62 cm). Overburden from the upper 15 cm of the substrate was collected in the core, thoroughly homogenized and transferred to clean plastic containers with a unique label applied to each sample. The sampler wore clean latex gloves. After collection, samples were kept cool and sent to the analytical laboratory in coolers with icepacks.

Samples were shipped to an external laboratory for analysis of total metals, pH, total organic carbon, basic nutrients and cations. Total metals were measured using inductively coupled plasma mass spectrometry (ICPS) (EPA Method 6010B), using procedures from CSR Analytical Method 8 "Strong Acid Leachable Metals (SALM) in Soil", BC Ministry of Environment, Lands and Parks, 26 June 2001, and procedures adapted from "Test Methods for Evaluating Solid Waste", SW-846 Method 3050B United States Environmental Protection Agency (EPA). pH analysis was carried out in accordance with procedures described in the pH, Electrometric in Soil and Sediment method - Section B Physical/Inorganic and Misc. Constituents, BC Environmental Laboratory Manual 2007. Total carbon was measured by combustion method (Nelson and Sommers 1996). Nitrogen content was determined by the combustion method (Bremner 1996) and/or by using the Kjeldahl method, which is the sum of ammonia (NH3) and ammonium (NH4+) present in the soil. Sulfur in soil was converted to a soluble form, where the free cations were quantified by ICPS (Tabatabai 1996). Cations were extracted by vacuum filtration and quantities determined by inductively coupled plasma optical emission spectrometry (ICP-OES) (Carter and Martin[a] 1993). Electrical conductivity was measured using a conductivity meter obtained from an extraction from a soil paste formed with deionized water (Carter and Martin[b] 1993). Overburden texture was determined according to procedures outlined in the Annual Book of ASTM Standards (2000). Samples were strained through a series of sieves to determine particle size distribution and percent fines. Texture analyses were performed in the Kemess South Mine soils laboratory.

Vegetation Measurements

All the plants in the study were assessed visually for survivorship after 60, 365, 425 days and 5 years of growth. Coinciding with the survivorship surveys, with exception of the 5-year survey, circular plots (radius = 0.13 m) were established around each seedling and used to visually determine percent cover of each plant. For the 365-day surveys, there were 3 plants measured per plot, whereas on the 425-day and 5-year surveys, the 2 plants remaining in each plot were measured.

For the 60-day and 365-day surveys, an average percent foliar cover of individual plants was calculated from the cover estimates of the 3 replicates within each plot. If there was a plant that did not survive, it was not included in the cover analysis. For the 425-day survey, the same methods were used with the exception an average of 2 replicates was used. Percent foliar cover was not assessed in the 5-year survey because the plant cover exceeded the plot area used in previous assessments.

After one year of growth, one plant was harvested from each plot on all topographic units on both blocks. For consistency, plant replicate 2 was harvested from each plot. If the middle plant in the plot had not survived, then it was omitted from subsequent analyses. If the other two plants in the plot had not survived, then no plant was harvested.

Lupine plants were sampled during the harvest to determine their biomass and root length and to assess their roots for nodule formations. Each lupine plant was clipped to ground level and the vegetative components were carefully placed in a sample bag and later oven dried for 48 hours at 80°C then weighed to obtain a dry mass. The roots were excavated, measured for length and placed in sample bags. After rinsing, the roots were visually assessed for the presence of root nodules (Figure 2.5). The cleaned roots were later dried and weighed. Total biomass was calculated by adding together above ground biomass and root biomass. Willow plants were sampled during the harvest to determine their root length. The willow plant was excavated and the root lengths were recorded.

Figure 2.5: Visual assessment of lupine roots for the presence of *Rhizobium* root nodules.

Statistical Analysis

Data were analyzed with SPSS 23 (SPSS, Inc., Chicago, IL, USA). Data were classified into four treatments: bottom swale (n = 15), slope-downhill (n = 15), slope uphill (n = 15) and top mound (n = 15) levels of topographical positions on the mounds. Differences in datasets among microtopographical positions were examined using one-way analysis of variance (ANOVA) with blocking by aspect. Because the experimental design was unbalanced (10 replicates on NW aspect and 5 on SW), an ANOVA with Type III sums of squares was used to test equality of means followed by Tukey's HSD when the ANOVA indicated a significant F-Value. Dependent variables were tested for assumptions of normality using the Shapiro-Wilk test for normality and a Levene's test for homogeneity of variances in SPSS. If required data transformations were conducted to better conform to the assumptions of an ANOVA.

Variables analyzed using the above statistical method include: overburden moisture, temperature, nutrient and physical parameters, as well as plant cover data, root mass, above ground biomass, total biomass, root length, plant height and stem diameter. Log transformations were conducted on the overburden moisture and temperature and root length, and square root transformations on biomass. Logit transformation were applied to plant cover data.

To determine survivorship by treatment for each time period (60-, 365-, 425-day, and 5-year), the data from plants 1 and 3 from each plot were used in a survival analysis. Life tables were completed to examine the distribution of survival among different treatments and a Cox regression analysis was used to assess the relationship between survival time and treatment. Pairwise log rank comparisons were conducted to determine which treatments had different survival distributions. This method was conducted for each species.

Lupine root nodule and flower presence data at one year were analyzed for differences in treatments using a Pearson's Chi-Square test (Miller and Siegmund 1982) for association in SPSS.

For purposes of presentation and ease of interpretation, the statistical analysis on the transformed data are reported but the data in the paper (text and figures) is presented in their original units.

Results

Overburden Moisture and Temperature

Near surface temperature taken at limited sampling times and when the sun was highest in the sky and with least potential for shade from microtopography were not different in 2010 or in 2011 (Table 2.1). However, there was a significant blocking effect in overburden temperatures measured in 2010 ($p<0.01$). Average near surface overburden moisture in 2010 and 2011 was statistically significantly different between different treatments. The difference in 2010 was attributable to differences in soil moisture in the bottom swales compared to all other topographical positions. Soil moisture readings in the bottom swales were much higher than the other treatments due to an accumulation of runoff water in the bottom swales after a precipitation event (Figures 2.6 and 2.7), which is consistent with results of similar studies (Munshower 1994). The gradient of average overburden moisture in 2010 increased from the top mound to the slope-downhill, slope-uphill and bottom swale topographical mound location, in that order. These results were consistent for the mean maximum moisture, mean minimum moisture, and mean average moisture for 2010 and 2011, with the exception that the mean average moisture in the top mound and slope-uphill were also statistically different in 2010. There was a significant blocking effect for all measures of overburden moisture ($p<0.01$).

Figure 2.6: Bottom swales of mounds inundated with water after precipitation event.

Figure 2.7: Bottom swale after standing water seeped into overburden.

Table 2.1: Mean near surface overburden temperature (°C), and moisture presented as water fraction by volume (wfv) in 2010 (n = 64; 4 treatments, 16 observations per treatment) and 2011 (n = 8; 4 treatments, 2 observations per treatment). All values are mean (± SE). Letters indicate significant differences between means within a row (Tukey HSD) at α=0.05.

Variable	Bottom Swale	Slope Downhill	Slope Uphill	Top Mound	P-Value
Soil Temperature (°C)					
Mean Average 2010	19.7 (0.1)	19.7 (0.1)	19.6 (0.1)	19.6 (0.1)	0.756
Mean Minimum 2010	10.1 (0.2)	10.0 (0.2)	10.1 (0.2)	10.0 (0.1)	0.854
Mean Maximum 2010	28.6 (0.2)	28.6 (0.2)	28.5 (0.2)	28.5 (0.2)	0.914
Mean Average 2011	21.0 (0.2)	21.0 (0.3)	20.9 (0.3)	20.9 (0.3)	0.982
Mean Minimum 2011	19.8 (0.3)	19.7 (0.4)	19.6 (0.4)	19.7 (0.4)	0.996
Mean Maximum 2011	23.0 (0.4)	22.9 (0.4)	22.8 (0.4)	22.8 (0.4)	0.957
Soil Moisture (wfv)					
Mean Average 2010	0.22 (0.02)[a]	0.13 (0.01)[bc]	0.15 (0.01)[b]	0.12 (0.01)[c]	<0.005
Mean Minimum 2010	0.09 (0.01)[a]	0.04 (0.003)[b]	0.05 (0.004)[b]	0.03 (0.003)[b]	<0.005
Mean Maximum 2010	0.47 (0.04)[a]	0.33 (0.01)[b]	0.35 (0.01)[b]	0.33 (0.13)[b]	<0.005
Mean Average 2011	0.24 (0.03)[a]	0.12 (0.01)[b]	0.13 (0.01)[b]	0.09 (0.004)[b]	<0.005
Mean Minimum 2011	0.17 (0.02)[a]	0.10 (0.01)[b]	0.10 (0.01)[b]	0.08 (0.004)[b]	<0.005
Mean Maximum 2011	0.32 (0.05)[a]	0.15 (0.01)[b]	0.16 (0.01)[b]	0.11 (0.01)[b]	<0.005

Overburden Characterization

The overburden physical properties characterized in 2009 prior to placement on the waste rock storage facility are presented in Table 2.2, showing average concentrations measured at the surface and at 1 m depth.

Because of the multiple testing of the overburden parameters measured in 2010 and 2015, the significance cut-off was conservatively set at $\alpha=0.01$ to reduce the probability of getting a significant result simply due to chance.

The majority of overburden physical properties measured in 2010 did not vary significantly among microtopographical positions, with the exception of electrical conductivity levels and the concentrations of potassium and sodium (Table 2.3). These differences were mostly attributable to the differences in levels occurring in the bottom swales compared to the other treatments. There was a significant blocking effect for measures of potassium ($p<0.001$), and sodium ($p=0.002$).

Concentrations of overburden variables measured in 2015 that varied significantly among microtopographical positions include total phosphorus, as well as available nutrients including nitrogen, phosphorus, potassium, manganese, and boron (Table 2.4). These differences were mostly attributable to the differences in concentrations occurring in the bottom swales compared to all other treatments. There was no significant blocking effect for overburden measures in 2015.

Table 2.2: Characterization of stockpiled overburden sampled at surface and 1 m depth in spring of 2009.

Parameter	Unit	Average Surface	Average 1m
Moisture	%	7.3	6.6
pH		7.5	7.7
Total			
Aluminum (Al)	mg/kg	12057	13231
Antimony (Sb)	mg/kg	0.4	0.4
Arsenic (As)	mg/kg	4.3	3.8
Barium (Ba)	mg/kg	125.7	154.8
Beryllium (Be)	mg/kg	0.3	0.3
Bismuth (Bi)	mg/kg	<0.1	<0.1
Cadmium (Cd)	mg/kg	0.30	0.22
Calcium (Ca)	mg/kg	13721	12846
Chromium (Cr)	mg/kg	17	15
Cobalt (Co)	mg/kg	9.5	9.8
Copper (Cu)	mg/kg	79.1	79.5
Iron (Fe)	mg/kg	21414	22986
Lead (Pb)	mg/kg	7.3	6.7
Magnesium (Mg)	mg/kg	6567	7051
Manganese (Mn)	mg/kg	519	559
Mercury (Hg)	mg/kg	<0.05	<0.05
Molybdenum (Mo)	mg/kg	0.7	0.9
Nickel (Ni)	mg/kg	14.9	13.4
Phosphorus (P)	mg/kg	453	457
Potassium (K)	mg/kg	565	575
Selenium (Se)	mg/kg	<0.5	<0.5
Silver (Ag)	mg/kg	0.09	0.09
Sodium (Na)	mg/kg	116	215
Strontium (Sr)	mg/kg	73.7	85.2
Thallium (Tl)	mg/kg	<0.05	0.06
Tin (Sn)	mg/kg	0.3	0.3
Titanium (Ti)	mg/kg	312	331
Vanadium (V)	mg/kg	47	53
Zinc (Zn)	mg/kg	54	50
Zirconium (Zr)	mg/kg	1.5	2.0

Parameter	Unit	Average Surface	Average 1m
Calcium Carbonate ($CaCO_3$-C)	%	0.21	0.22
Organic C	%	0.37	0.30
Carbon (C)	%	0.58	0.52
Nitrogen (N)	%	0.03	0.02
Sulphur (S)	%	0.018	0.017
Available Nutrients in Overburden Solution			
Phosphorus (P)	ppm	5	4
Potassium (K)	ppm	72	56
Calcium (Ca)	ppm	3686	3929
Magnesium (Mg)	ppm	177	229
Sulphate (SO_4-S)	ppm	5.4	10.6
Exchangeable Cations			
Cation Exchange Capacity (CEC)	cmol/kg	19.7	21.3
Calcium (Ca)	cmol/kg	21.5	22.8
Magnesium (Mg)	cmol/kg	1.86	2.19
Sodium (Na)	cmol/kg	0.14	0.38
Potassium (K)	cmol/kg	0.29	0.23

Table 2.3: Characterization of near surface overburden sampled from the study site at Kemess Mine's waste rock storage facility in summer 2010 (n = 16; 4 treatments, 4 replicates per treatment). All values are mean (± SE). Significant one-way ANOVA models are presented in bold. Letters indicate significant differences between means within a row (Tukey HSD) at α=0.01.

Parameter	Unit	Bottom Swale	Slope - Downhill	Slope- Uphill	Top Mound	P-Value
pH		8.1 (0.1)	8.0 (0.1)	8.2 (0.1)	8.0 (0.1)	0.563
Electrical Conductivity (EC)	**dS/m**	**0.37 (0.01)[a]**	**0.25 (0.01)[b]**	**0.29 (0.01)[b]**	**0.26 (0.01)[b]**	**<0.001**
Organic Matter (OM)	%	2.0 (0.2)	2.6 (0.3)	2.4 (0.3)	2.5 (0.3)	0.132
Available Nutrients in Overburden Solution						
Nitrogen (N)	ppm	1 (0)	1 (0)	1 (0)	1 (0)	n/a
Phosphorus (P)	ppm	6 (0)	5 (0)	5 (0)	6 (0)	0.083
Potassium (K)	**ppm**	**78 (5)[ac]**	**64 (3)[b]**	**71 (5)[ad]**	**73 (3)[acd]**	**0.002**
Sulfur (S)	ppm	7 (2)	3 (0)	4 (1)	3 (0)	0.054
Calcium (Ca)	ppm	4610 (499)	3798 (318)	3970 (462)	3833 (410)	0.126
Magnesium (Mg)	ppm	160 (24)	147 (15)	150 (20)	150 (19)	0.961
Sodium (Na)	**ppm**	**136 (18)[a]**	**60 (8)[b]**	**83 (12)[b]**	**63 (17)[b]**	**0.001**
Exchangeable Cations						
Calcium (Ca)	cmol/kg	23.0 (0.1)	19.0 (0.0)	19.8 (0.0)	19.1 (0.1)	0.121
Magnesium (Mg)	cmol/kg	1.3 (0.1)	1.2 (0.0)	1.2 (0.0)	1.2 (0.1)	0.959
Sodium (Na)	**cmol/kg**	**0.6 (0.0)[a]**	**0.2 (0.0)[b]**	**0.3 (0.1)[b]**	**0.2 (0.1)[b]**	**0.004**
Potassium (K)	cmol/kg	0.20 (0.01)	0.17 (0.01)	0.18 (0.02)	0.19 (0.01)	0.012
Total Exchange Capacity (TEC)	cmol/kg	25.1 (2.7)	20.6 (1.8)	21.6 (2.5)	20.8 (2.3)	0.097
Sand	%	75.1 (2.9)	70.9 (2.8)	71.9 (3.3)	72.0 (3.3)	0.492
Silt	%	19.2 (2.9)	22.2 (2.5)	21.2 (2.2)	21.1 (2.2)	0.365
Clay	%	5.75 (0.8)	7.0 (0.4)	7.0 (2.1)	7.0 (0.4)	0.851

Table 2.4: Characterization of near surface overburden sampled from the study site at Kemess Mine's waste rock storage facility in summer 2015 (n = 16; 4 treatments, 4 replicates per treatment). All values are mean (± SE). Letters indicate significant differences between means within a row (Tukey HSD) at α=0.01.

Parameter	Unit	Bottom Swale	Slope - Downhill	Slope - Uphill	Top Mound	P-Value
pH		8.1(0.1)	8.2(0.1)	8.3(0.1)	8.2(0)	0.458
Electrical Conductivity	dS/m	0.2(0.0)	0.2(0.0)	0.2(0.0)	0.2(0.0)	n/a
Organic Matter(OM)	%	1.1(0.1)	1.3(0.0)	1.2(0.0)	1.5(0.1)	0.018
Total						
Aluminum (Al)	%	7.43(0.1)	7.38(0.12)	7.44(0.08)	7.32(0.06)	0.752
Antimony (Sb)	mg/kg	2.56(0.21)	2.58(0.4)	3.42(0.32)	2.69(0.57)	0.381
Arsenic (As)	mg/kg	36.2(3.7)	40.5(10.5)	65.6(10.2)	49.3(13.6)	0.247
Barium (Ba)	mg/kg	703(9)	708(6)	678(13)	703(19)	0.410
Beryllium (Be)	mg/kg	0.92(0.01)	0.92(0.02)	0.91(0.03)	0.89(0.02)	0.548
Bismuth (Bi)	mg/kg	0.16(0)	0.16(0.01)	0.18(0)	0.16(0.02)	0.431
Cadmium (Cd)	mg/kg	0.82(0.07)	0.74(0.14)	1.01(0.1)	0.77(0.18)	0.435
Calcium (Ca)	%	2.05(0.02)	2.11(0.09)	2.15(0.05)	2.09(0.08)	0.715
Chromium (Cr)	mg/kg	52(1)	53(3)	58(2)	56(1)	0.169
Cobalt (Co)	mg/kg	18.9(0.8)	18.8(1.8)	22.1(1.2)	18.9(2.3)	0.381
Copper (Cu)	mg/kg	212.9(23.6)	159.4(38.7)	187.8(25.5)	125.8(30.2)	0.111
Iron (Fe)	%	4.34(0.11)	4.34(0.24)	4.66(0.13)	4.29(0.27)	0.508
Lead (Pb)	mg/kg	30.4(7.1)	21.5(3.3)	38.4(7.4)	24.3(4.9)	0.250
Magnesium (Mg)	%	1.38(0.05)	1.37(0.1)	1.45(0.05)	1.33(0.1)	0.620
Manganese (Mn)	mg/kg	1278(64)	1242(144)	1545(102)	1288(164)	0.309
Molybdenum (Mo)	mg/kg	1.68(0.07)	1.98(0.36)	1.85(0.14)	1.45(0.22)	0.439
Nickel (Ni)	mg/kg	20.8(0.8)	20.8(0.9)	23(0.5)	20.7(1.1)	0.147
Phosphorus (P)	**mg/kg**	**885(36)[a]**	**758(15)[b]**	**748(17)[b]**	**732(9)[b]**	**<0.001**

Parameter	Unit	Bottom Swale	Slope - Downhill	Slope - Uphill	Top Mound	P-Value
Potassium (K)	%	1.18(0.02)	1.13(0.03)	1.14(0.03)	1.1(0.01)	0.121
Silver (Ag)	mg/kg	0.18(0.02)	0.18(0.02)	0.7(0.48)	0.2(0.03)	0.373
Sodium (Na)	%	1.64(0.03)	1.68(0.11)	1.61(0.05)	1.75(0.11)	0.643
Strontium (Sr)	mg/kg	317.8(5.9)	328(9.4)	310.5(6.2)	336.5(14.8)	0.260
Thallium (Tl)	mg/kg	0.36(0.02)	0.35(0.03)	0.42(0.02)	0.35(0.03)	0.170
Titanium (Ti)	%	0.437(0)	0.438(0.006)	0.445(0.004)	0.441(0.005)	0.629
Vanadium (V)	mg/kg	143(4)	141(8)	154(4)	141(9)	0.419
Zinc (Zn)	mg/kg	143(12)	133(17)	170(12)	137(24)	0.384
Zirconium (Zr)	mg/kg	71.6(0.9)	73.7(1.3)	71(0.9)	73.4(2.5)	0.539
Available Nutrients in Overburden Solution						
Nitrogen (N)	**ppm**	**9(2)[a]**	**3(0)[b]**	**5(1)[ab]**	**2(0)[b]**	**0.004**
Phosphorus (P)	**ppm**	**24(4)[a]**	**4(2)[b]**	**2(0)[b]**	**3(1)[b]**	**0.001**
Potassium (K)	**ppm**	**119(11)[a]**	**71(10)[b]**	**79(8)[b]**	**61(5)[b]**	**0.001**
Sulfur (S)	ppm	4(1)	4(1)	3(0)	3(0)	0.308
Copper (Cu)	ppm	19.7(2.7)	11.4(3.9)	10.2(2.7)	6(2.1)	0.013
Manganese (Mn)	**ppm**	**10.9(0.8)[a]**	**8.1(0.3)[b]**	**8.7(0.5)[b]**	**7.1(0.7)[b]**	**0.001**
Zinc (Zn)	ppm	2.4(0.6)	1(0.1)	1.5(0.2)	1(0.2)	0.044
Boron (B)	**ppm**	**0.8(0.0)[a]**	**0.4(0.0)[b]**	**0.6(0.0)[c]**	**0.3(0.0)[b]**	**<0.001**
Iron (Fe)	ppm	21(1)	24(1)	22(1)	23(1)	0.314
Chlorine (Cl)	ppm	3(0)	2(0)	3(0)	3(0)	0.024

Lupine

Survival

Life tables were completed to examine the distribution of survival among different treatments and a Cox regression analysis was used to assess the relationship between survival time and treatment. The lupine survival curve showing the effect of each treatment is presented in Figure 2.8. The Cox regression comparing survival distributions among treatments concludes that the survival curves are different across treatments ($p<0.001$). Pairwise comparisons indicate that there was a statistically significant difference in survival distributions for the bottom swale and slope-uphill treatments, $\chi 2(1) = 15.332$, $p < 0.001$, and top mound treatments, $\chi 2(1) = 11.407$, $p < 0.001$. There was also a significant difference between slope-downhill and slope-uphill treatments, $\chi 2(1) = 5.154$, $p = 0.023$. The statistical difference in survival distributions for the bottom swale and slope-downhill treatments was significant at a p-value of < 0.1, $\chi 2(1) = 3.584$, $p = 0.058$. In summary, lupine survival was lower in the bottom swale treatment than all other treatments and survival in the slope-downhill treatment was significantly lower than the top mound treatment.

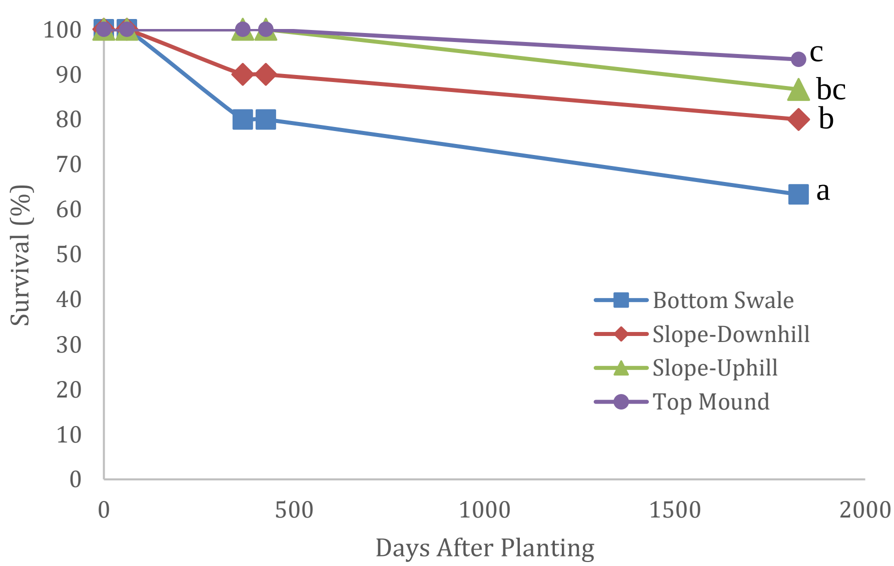

Figure 2.8: Lupine survival distribution displaying survival of plants in each treatment over a 5-year period after planting, n =60; 4 treatments, 15 replicates per treatment. Significant differences in survival among treatments at year 5 are indicated by different letters.

Cover

Average cover after 365 days and 425 days differed by treatment and Tukey post hoc analysis revealed that the bottom swale treatment was lower in cover than all the other treatments (Figure 2.9).

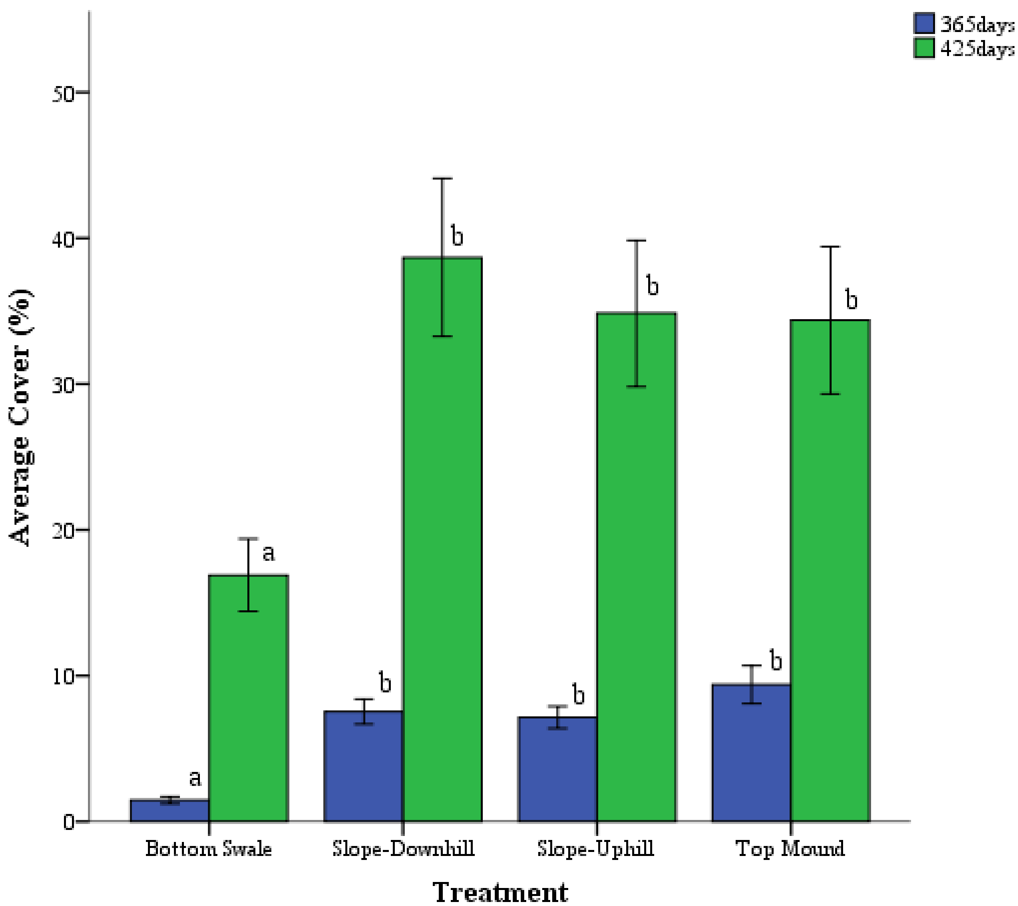

Figure 2.9: Mean foliar cover of lupine plants 365 and 425 days after planting by microtopographical position (n = 60; 4 treatments, 15 replicates per treatment). Bar heights indicate mean percent cover, arrows indicate SE. Letters indicate significant differences in cover among treatments within each year (Tukey HSD) at α=0.05.

Lupine Growth Parameters

After 365 days of growth lupine root mass, above ground biomass, total biomass, root length, and flower and nodule presence were assessed (Table 2.5). The average lupine root mass after 365 days was not impacted by treatment. However, above ground biomass was lower in the bottom swale versus slope downhill and top mound treatments. Total biomass was also impacted by treatment with the bottom swale location resulting in lower biomass production than the top mound. The same results were found for root length which was significantly lower in the bottom swale than for plants grown on the top of the mound. Flower presence was not significantly impacted by treatment but nodule presence was significantly lower in the bottom swale than all other treatment locations. In general, there were no significant blocking effects for lupine growth parameters.

Table 2.5: Lupine plant growth parameters at 365 days' growth. n = 60; 4 treatments, 15 replicates per treatment. All values are mean ± SE. Significant one-way ANOVA models are presented in bold. Letters indicate significant differences between means within a row (Tukey HSD) at α=0.05.

Variable	Unit	Bottom Swale	Slope Downhill	Slope Uphill	Top Mound	P-Value
Root Mass	g	0.64 (0.11)	0.86 (0.08)	0.73 (0.11)	1.04 (0.14)	0.081
Above Ground Biomass	**g**	**0.40 (0.09)^{a}**	**0.88 (0.11)^{b}**	**0.87 (0.18)^{ab}**	**1.10 (0.19)^{b}**	**0.005**
Total Biomass	**g**	**1.04 (0.20)^{a}**	**1.74 (0.19)^{ab}**	**1.60 (0.27)^{ab}**	**2.15 (0.32)^{b}**	**0.024**
Root Length	**cm**	**10.2 (1.8)^{a}**	**15.1 (0.9)^{ab}**	**12.9 (1.5)^{ab}**	**17.5 (1.4)^{b}**	**0.006**
Flower Presence	%	4.4	11.1	8.9	13.3	0.518
Nodule Presence	**%**	**33.3^{a}**	**80^{b}**	**93.3^{b}**	**93.3^{b}**	**0.0002**

Willow

Survival

Life tables were completed to examine the distribution of survival of willow plants among different treatments and a Cox regression analysis was used to assess the relationship between survival time and treatment. The willow survival curve showing the effect of each treatment is presented in Figure 2.10. The Cox regression test comparing survival distributions among treatments concludes that the survival curves were different across treatments ($\chi2(2) = 14.365$, $p < 0.002$). Pairwise comparisons indicate a difference in survival distributions for the bottom swale and slope-uphill treatments, $\chi2(1) = 4.288$, $p = 0.038$, bottom swale and top mound treatments, $\chi2(1) = 5.259$, $p = 0.022$, bottom swale and slope-downhill treatments, $\chi2(1) = 5.259$, $p = 0.022$. In summary, willow survival was lower in the bottom swale treatment than all other treatments.

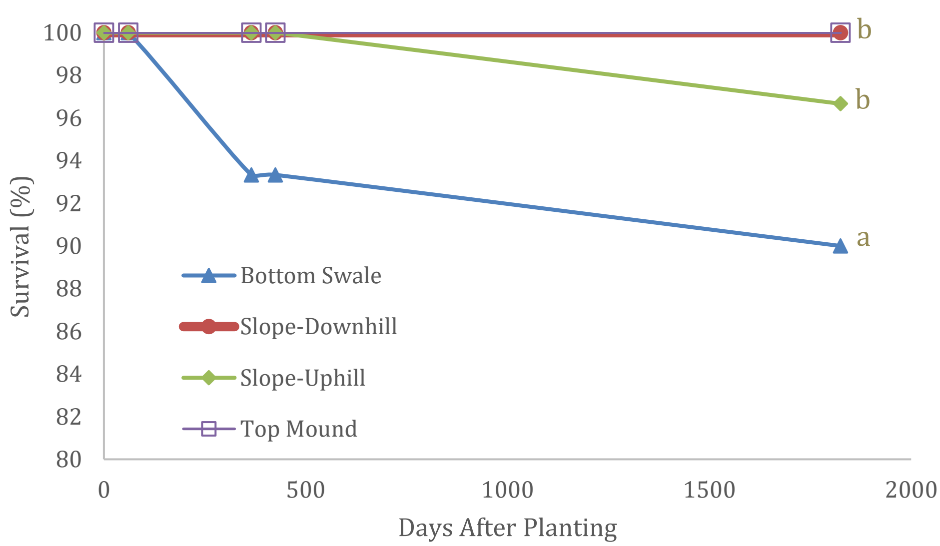

Figure 2.10: Willow survival distribution displaying survival of plants in each treatment over a 5-year period after planting, n = 60; 4 treatments, 15 replicates per treatment. Significant differences in survival among treatments at year 5 are indicated by different letters. Slope downhill and top mound treatments had 100% survival and lines overlap.

Willow Cover

Average foliar willow cover after 365 days was impacted by planting location and was lower on the bottom swale location than the slope downhill location (Figure 2.11). At 425 days the cover of willow had increased and willow cover in the bottom swale treatment was higher than the slope uphill and top mound treatments (Figure 2.11).

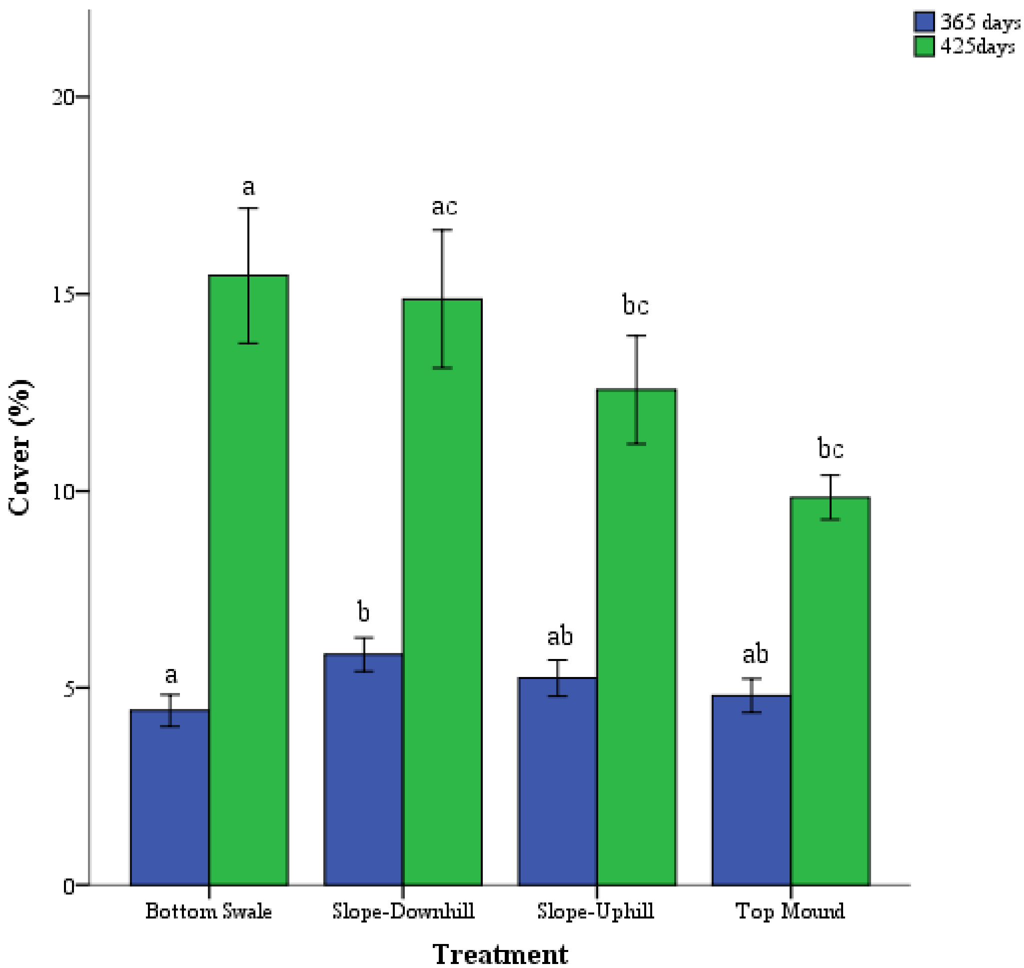

Figure 2.11: Mean foliar cover of willow plants 365 and 425 days after planting by microtopographical position (n = 60; 4 treatments, 15 replicates per treatment). Bar heights indicate mean percent cover, arrows indicate SE. Letters indicate significant differences in mean cover among treatments within each year (Tukey HSD) at α=0.05.

Willow Height

There was no difference between treatments in mean willow height after 60 days, 425 days and 5 years (Figure 2.12). However, at 365 days willows grown in the bottom swale treatment were shorter than those on the slope downhill and uphill treatments. Willow height was substantially higher (more than double in all treatments) by 5 years.

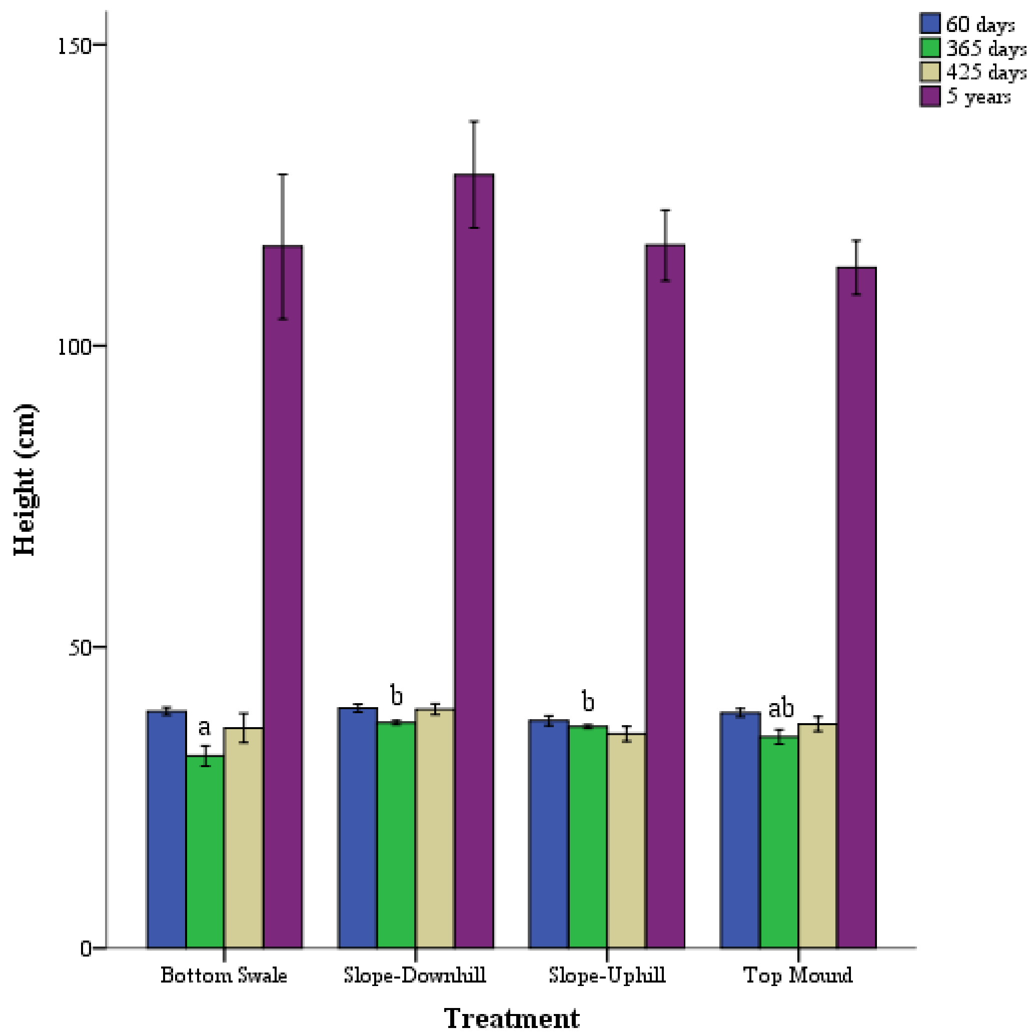

Figure 2.12: Willow height at 60, 365, 425 days' and 5 years' growth (n= 60; 4 treatments, 15 replicates per treatment). Bar heights indicate willow height (cm), arrows indicate SE. Letters indicate significant differences in height among treatments within each year (Tukey HSD) at α=0.05.

Willow Growth Parameters

After 365 days of growth willow root length and stem diameter were assessed (Table 2.6). Willow root length was shorter for willows in the bottom swale location versus all other treatment locations. Stem diameter was not impacted by treatment. In general, there were no significant blocking effects for willow growth parameters.

Table 2.6: Willow growth variables at 365 days (n = 60; 4 treatments, 15 replicates per treatment). All values are mean ± SE. Letters indicate significant differences between means within a row (Tukey HSD) at α=0.05.

Variable	Unit	Bottom Swale	Slope Downhill	Slope Uphill	Top Mound	P-Value
Root Length	cm	13.5 (1.6)^{a}	22.0 (1.3)^{b}	20.3 (1.5)^{b}	20.2 (1.0)^{b}	0.003
Stem Diameter	mm	11.2 (0.2)	11.4 (0.2)	11.0 (0.3)	11.1 (0.3)	0.59

Discussion

Overburden is an important segment of the mine reclamation process. The physical, chemical and biological properties of overburden serve as the resources for plant establishment and growth of a reclaimed ecosystem. The results of this study highlight how the physical, chemical, and biological properties of overburden can be altered through the application of mounded microtopography, creating microsite conditions that influence the survival and growth of planted seedlings. Furthermore, this study highlights the importance of microsite conditions in the context of mine reclamation.

Objective 1 – Does near surface overburden temperature and moisture respond to mounding?

The overburden moisture and temperature data collected in this study are specific to the geographic location of the study area and to the climatic conditions experienced during the timeframe of the study. Moisture and temperature data points are from a single time in the day and therefore do not capture daily fluctuations. Also, the remote location of the study site made it challenging to obtain moisture and temperature data points throughout the entire field season, with 16 samples days occurring in 2010 and 2 sample days occurring in 2011.

Near surface temperature response has been reported to be site specific with results varying by year (Peterson et al. 1990). Knapp et al. (2008) did not detect significant differences in soil surface temperature measurements among the different mounding treatments in a forestry setting in one year, but did detect differences the second year of the study (Knapp et al. 2008). In forestry settings, top mounds have been found to have higher surface soil temperatures (Walker and del Moral 2003, Löf and Birkedal 2009) and greater seasonal surface soil temperature fluctuations than bottom swales (Beatty 1984, Price et al. 1998, Bilodeau-Gauthier et al. 2013). Near surface overburden temperature results from this study did not detect a difference in mound topographical position throughout the summer months. This could be due to overburden's lack of organic layer that occurs in forestry soils; when mounded, the surface organic layer is inverted and capped by mineral soil that is exposed above the ground surface, and contributes to elevated soil temperatures (McMinn 1985, Sutton 1993, Londo and Mroz 2001). Although this study did not look at seasonal trends in overburden temperature, it was observed that snow melted from the top mounds earlier than it did in the bottom swales during the spring melt, potentially meaning an extended growing season on the top mounds, which is consistent with other findings (Beatty 1984, Price et al. 1998). If an alternate method had been used to measure overburden temperature, such as instrumentation that continuously logs temperature at set intervals over longer periods, then perhaps differences in overburden temperature would have been identified during this study. This assertion is supported by the continuous logging of air temperature and light measured at the surface of each treatment in the summer and fall of 2015, which recorded significant differences in maximum summer temperature as well as average summer and fall light and maximum summer light (Appendix B).

Overburden moisture in the bottom swales was wetter than the other microtopographical positions, with an average moisture content of 22% in 2010 and 2011, compared to a range of 9-15% in the other treatments. This result is not unexpected due to the accumulation of water that occurs in the bottom swales. These results are consistent with hydrologic conditions observed in natural and restored wetlands (Bruland

and Richardson 2005), forests (Levy-Booth 2016) and grasslands with created microtopography (Hough-Snee et al. 2011). Top mounds have been found to be drier, with lower snow cover than bottom swales (Beatty 1984, Price et al. 1998). During the summer, average overburden moisture content in a waste dump of 2-3% was found to be sufficient for plant growth (Maiti et al. 2002), whereas Maiti and Ghose (2005) found the average to be 5%. The top treatment recorded an average minimum moisture content of 3% in 2010, indicating that it may be the most susceptible to moisture deficits, particularly in drier years. The significant differences in near surface overburden moisture were sufficiently different to affect seedling growth and survival as it has been shown that soil moisture preferences differ by species and functional group (Hough-Snee et al. 2011). Therefore, mounding may be a tool used to facilitate the ingress of both drought-tolerant and flood-tolerant plant species.

Objective 2 – Does mounding impact nutrient availability and texture?

In general, overburden tends to be found deficient in essential plant nutrients such as nitrogen, phosphorus, and potassium (Sheoran et al. 2008; Sheoran et al. 2010), which is consistent with the nutrients measured in the overburden of this study. In 2010, nitrogen, phosphorus, and potassium levels were measured to be deficient in all treatments except for potassium in the bottom swale, which was slightly higher, but still considered to be low (Munshower 1994). In 2015, there was an increase in nutrient concentrations measured in the bottom swales, achieving levels that do not require amendments (Munshower 1994). However, the concentrations measured in all other treatments in 2015 were still considered deficient (Munshower 1994). Overburden with sandy texture, such as the material in this study, is limited in the quantity of water and nutrients it can hold, in comparison to finer textured material (Sheoran et al. 2010). However, as mounds subside, fine-textured overburden sediments may accumulate in the swale of a mound (Beatty and Stone 1986; Leavitt et al. 2000), contributing to an accumulation of water and nutrients in the bottom swale (Kooch et al. 2015). Correspondingly, bottom swales have been found to have higher nutrients, organic matter, and cation exchange capacity than top mounds (Beatty 1984, Price et al. 1998). The results of this study were consistent with the findings of similar studies where higher concentrations of nutrients

(N, P, K, S, Cu, Mn, Zn, and B) were observed in the bottom swales. The difference in soil chemistry in mounds and swales is likely the result of the accumulation of leaching nutrients in the bottom swales displaced from the top and slopes of mounds.

The results of the trace metal analyses conducted in 2009 and 2015 were compared against the accepted soil quality guidelines for industrial and agricultural sites (CCME 2017) to identify any exceedances. There were no exceedances of industrial site guidelines detected in the overburden sampled in 2009. However, the copper measured in the overburden in 2009 exceeded the recommended level of copper (63 mg/kg) for agricultural sites (CCME 2017). Furthermore, the results of the 2015 samples for all treatments exceeded the recommended allowable levels on industrial sites and agricultural sites for arsenic (12 mg/kg), copper (91 mg/kg, 63 mg/kg), and vanadium (130 mg/kg) (CCME 2017). These three elements have also been measured to be elevated in nearby natural undisturbed soils (Evans 2016). Copper toxicity in soils is generally not a concern in minesoils unless the soil is acidic (Munshower 1994), which is not the case on Kemess' waste rock storage facility. Elevated concentrations of arsenic are commonly associated with metal mines and ore bodies containing arsenic (Munshower 1994). Compounds of arsenic can be toxic to plants and animals and were previously used as herbicides and pesticides (Munshower 1994). Therefore, the elevated arsenic concentrations measured in the overburden sampled in the study area may have negatively influenced plant growth, at least to some extent. Compounding the potential arsenic effect, elevated concentrations of vanadium have been shown to reduce plant biomass by 50% (Smith et al. 2013).

Copper, manganese, zinc, boron, iron, molybdenum, and chlorine are essential micronutrients for plant growth. Their availability in overburden is directly attributed to the breaking down of minerals present in the material. This study found higher available metallic micronutrients (Cu, Mn, Zn, and B) in the bottom swales, likely the result of an accumulation of leaching and displacement from the mounds. Metallic micronutrients may be more bioavailable in the bottom swales, which could result in toxicity to some plants growing in the bottom swales (Barcelo and Poshenrieder 2003). However, the literature is inconclusive about what concentrations of micronutrients result in toxicity as symptoms of toxicity vary by species and individuals (Kabata-Pendias and Pendias 2001).

Concentrations of available copper measured in the overburden sampled in 2015 ranged from 6 mg/kg in the top mound to 19.7 mg/kg in the bottom swale. These levels are within the normal range of available copper measured in soils (Kabata-Pendias and Pendias 2001). Available manganese levels measured in 2015 ranged from 7.1 mg/kg in the top mound to 10.9 mg/kg in the bottom swale, showing no concerns for critical deficiencies (Kabata-Pendias and Pendias 2001). Concentrations of available zinc measured in 2015 ranged from 1.0 mg/kg in the top mound to 2.4 mg/kg in the bottom swale. A critical deficiency limit in soil identified for zinc as 1.0 mg/kg (Munshower 1994, Kabata-Pendias and Pendias 2001), indicating that the top mounds may be subject to deficiencies in zinc. Available boron concentrations measured in 2015 ranged from 0.3 mg/kg in the top mound to 0.8 mg/kg in the bottom swale. The top mounds may also be subject to boron deficiencies at levels of 0.1-0.3 mg/kg ((Kabata-Pendias and Pendias 2001).

Previous studies on mounds in a forestry setting have shown that differences in organic matter observed between the top mound and bottom swales have been variable and may be influenced by age of the microtopographical feature (Liechty et al. 1997). To create a mound, a portion of forest floor and underlying mineral soil is inverted and placed on top of an adjacent area of undisturbed forest floor, exposing mineral soils in the bottom swale and depositing a mixture of mineral soil and organic matter on the mound. Younger mound features have been found with lower levels of organic matter in the bottom swales compared with the top mounds (Beatty and Stone 1986). Whereas, in older mounds, studies found higher levels of organic matter located in the bottom swales (Liechty et al. 1997, Kooch et al. 2015). This study supports these previous findings in that the relatively young mounds examined in this study measured lower organic matter in the bottom swales in 2010 and 2015. Soil organic matter measured in 2010 were low (Munshower 1994), ranging from 2 % in the bottom swale to 2.6% on the Slope-downhill. There was a slight decrease in soil organic matter measured in 2015, with measurements ranging from 1.1 % in the bottom swale to 1.5 % in the top mound, which were all very low (Munshower 1994). These findings contrast with the increases in surface organic matter that forestry sites may experience within the first few years after disturbance resulting from the forest residues remaining in the soil after harvest (Packer and Williams 1976, Cromack et al. 1979). However, on sites lacking forest residues in the soil, like in overburden, decreases in organic matter as new vegetation develops is consistent with previous reports (Kraemer and Hermann 1979, Durgin 1980). This may be an outcome of created microsite conditions conducive to increased activity of soil microorganisms and organic matter decomposition rates (Hendrickson et al. 1982, Benson 1982). However, it is expected that organic matter will accumulate at higher rates in the bottom swales over time because of the high moisture content occurring in the bottom swales that may be sufficient to inhibit aerobic decomposition of litter (Bruland and Richardson 2005).

Objective 3 – What were the impacts of mounding on plant growth and survival?

This study confirmed that created microtopography influences plant survival and growth on a mine reclamation site, resulting at least in part from the differences in overburden habitat conditions occurring due to the microtopography formed by the surface preparation technique of mounding. This assertion is supported by similar forestry-related studies on mounds (Peterson et al. 1990; Bruland and Richardson 2005; Löf et al. 2006; Gilland and McCarthy 2013). Results from one forestry study indicated that site preparation techniques such as mounding influenced growth of seedlings, however it did not affect survival in comparison to an untreated (control) site (Bedford and Sutton 2000). It is important to note that the commercial growing medium within the nursery-grown plugs used in the study may have obscured some of the plant growth and survival results of the study due to the enriched local conditions associated with the growing medium. These enriched conditions likely attributed to the high overall survival of the seedlings.

Lupine

Total lupine seedling survival after 5 years was 81%, which is much higher than values measured in previous studies looking at planted lupine seeds with survival rates ranging from 6-50% after one year (Bowles et al. 1997, Pavlovic and Grundel 2008), and

23% of transplanted lupine seedlings (Bowles et al. 1997). The higher survival rates measured in this study are likely attributed to the enhanced root system developed at the nursery prior to planting in the field, together with the enriched conditions within the commercial growing medium used in the plugs planted in this study.

Functional group composition of a developing plant community is influenced by microsite conditions resulting from microtopographical positions of mounds (Hough-Snee et al. 2011). The general pattern of lower lupine growth and survival in the bottom swale recorded in this study is consistent with observations at other sites that found that nitrogen-fixing species preferred top mounds (Gilland and McCarthy 2013). Nitrogen-fixing species may suffer from the increased resource retention, such as water and nutrients, in the bottom swales. Furthermore, lupine species may be sensitive to the elevated bioavailability of metallic micronutrients occurring in the bottom swales, which has been found to be toxic to some plants (Barcelo and Poshenrieder 2003; Das and Maiti 2006, Sheoran et al. 2010).

Biomass has been used as a gauge of plant stress to the environment, with lower biomasses occurring in stressful environments (Davidson 1969; Struik and Bray 1970, Del Moral and Titus 1998). Applying this indicator to the results of this study suggest that lupine species are inhibited by the habitat conditions occurring in the bottom swales, in which the lowest biomass, cover and survival were observed.

Bacterial abundance is generally positively correlated with quantity of organic matter (Prevost-Boure et al. 2011, Wang et al. 2013, Levy-Booth 2016), which is consistent with the *Rhizobium* nodule presence found in this study (i.e. lower organic matter in the bottom swales and lowest presence of *Rhizobium* nodules in the bottom swales). The presence of *Rhizobium* bacteria in lupine roots has been shown to enhance lupine seedling survival rates (Bowles et al. 1997). Therefore the lack of symbiotic *Rhizobium* nodules occurring on the roots of lupine plants growing in the bottom swales may have attributed to lower lupine survival rates in that location.

The absence of lupine *Rhizobium* nodules observed on plant roots in some of the bottom swales after the first year of growth suggests that overburden physical and chemical properties (i.e. elevated moisture and nutrients in bottom swales) occurring due to mounding, may also influence the structure of bacterial communities in the overburden of a metal mine waste rock storage facility. Recent forestry studies found that soil moisture distinctly affected bacterial community structure (Brockett et al. 2012), but not bacterial abundance (Levy-Booth 2016). Whereas, Lauber et al. (2008) found no effects of soil moisture on bacterial community structure (Lauber et al. 2008). Studies have also shown that *Rhizobium* nodule formation on legume roots is inhibited by salt stress (El-Shinnawi et al. 1989, Velagaleti et al. 1990, Zahran 1991), which refers to elevated levels of soluble salts in the root zone, including ions of sodium and potassium. Nodule formation can be completely suppressed at some levels of salt stress, ultimately decreasing the amount of N_2 fixed by legumes (Zahran 1999). Consistent with previous works, the significantly higher levels of sodium and potassium ions measured in the bottom swales in this study suggest that salt stress may distort lupine *Rhizobium* nodule formation. Nodule presence may also be inhibited by the higher levels of nitrogen measured in the bottom swales (Carroll and Gresshoff 1983; Streeter and Wong 1988). It has also been shown that *Rhizobium* bacteria are sensitive to increases in some metals, such as copper, zinc, nickel, cadmium, lead and chromium (Kabata-Pendias and Pendias 2001). One study measured a significant reduction in N-fixation in *Rhizobium* bacteria when exposed to increased levels of these metals (McGrath et al. 1994). Considering the significantly higher concentrations of available zinc and copper measured in the bottom swales may indicate that one or both parameters exceeded a threshold causing adverse effects to occur on *Rhizobium* bacteria.

It should be noted that the root nodule data in this study are specific to commercially grown nursery seedlings where the inoculation of *Rhizobium* may have occurred. It is not known if the overburden studied contains a native population of *Rhizobium* bacteria. Furthermore, the root nodule, root length, flower, stem diameter and biomass data in this study are from a single date and therefore do not capture temporal fluctuations.

Willow

Overall willow plug survival rates (97%) measured in this study after 5 years since planting demonstrated a high benchmark for seedling success. This assertion is supported by previous findings, such as in the planting program in the Elkview

Operations in Sparwood BC, which demonstrated a willow seedling survival of 80-90% 3 years after planting on a waste rock storage facility (Przeczek and Amos 2014).

In the current study, microtopographic features, at least initially, did influence the survival and growth of willow species. Contrary to expectations, the survival and cover were lower for willow planted in bottom swales compared with survival and cover on the mounds in the first year. Some willow species are restricted to wetland and floodplain habitats, requiring constant moisture. However, it has been demonstrated that for some willow species constant moisture is only critical for willow seed germination and less important after seedling establishment (McLeod and McPherson 1973; Argus 1986; Skvortsov 1999; Kuzovkina and Volk 2009). In the second year of growth, willows planted in the bottom swales had significantly higher cover than locations on the mound which is more in line with the rapid growth rate and high tolerance for saturated soils demonstrated by many *Salix* species (Kuzovkina and Volk 2009). Higher growth in the bottom swales is consistent with results of a similar study on wetland species (Bruland and Richardson 2005).

Microtopographical features have considerable effects on the extension of the root system and above ground performance of willow seedlings, at least in the first year of growth. In the first year of growth, root length was higher for willow planted on the mounds while cover was lower, in comparison to willow planted in the bottom swales. This supports previous experimental results, which focused on mounding effects on seedling growth of oak trees (Löf et al. 2006). In this study, moisture and some nutrient concentrations were lower on the mounds in comparison with the bottom swales which could account for the higher willow rooting depths observed on the mounds, at least in the first year of growth (Shipley and Meziane 2002, Cahill 2003). Moreover, decreased rooting depth in the bottom swales may be an indication that saturated sites like in the bottom swales may be conducive to lateral root growth (Lyr and Garbe 1995; Lyr 1996; Bolte and Löf 2010), which contributed to the higher cover in the bottom swales after the first 2 years of growth.

Conclusion

The created microtopography within the mounding treatments on the waste rock storage facility of a former metal mine facilitated significant differences in physical, chemical, and biological microsite conditions as well as plant survival and growth, at least in the first few years after planting. Created microtopography may be an efficient tool in influencing overburden features and increasing the diversity of colonizing plant species on a mine reclamation site by providing a variety of sites favorable for seedling development. Mounding can be used as a tool to increase site heterogeneity and drive plant community development. Furthermore, mounding may play a role in shaping bacterial community structure. This suggests that the surficial microtopography applied when reclaiming a waste rock storage facility can be prescribed to facilitate a variety of distinct habitat conditions to accommodate habitat requirements for a diversity of plant functional groups and microbial communities.

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CHAPTER 3 - RESEARCH SUMMARY AND MANAGEMENT IMPLICATIONS

All mines in British Columbia are required to plan for closure and to take measures to synthesize stable and productive post-closure landscapes that are conducive to predetermined end land uses (BC MEM 2016). The aim of reclaiming a mine site is to stabilize components (Wong 2003) and processes (Singh et al. 2002, Lone et al. 2008, Kavamura and Esposito 2010) of the severely disturbed site to a contemporary standard and/or on a trajectory towards a desired future ecosystem state (Sheoran et al. 2010, Palmer and Ruhl 2015). Reclamation efforts must ensure that the surface preparation and vegetative cover applied can meet the objectives of stabilization and defined end land uses. The overburden resource allocated as a growing medium for application in mine reclamation projects is inherently degraded in its chemical, physical and biological properties (Ghose 2002, Sheoran et al. 2010) in comparison to native soils. Therefore, in the context of reclaiming a waste rock storage facility of a former metal mine, it is important to manage the overburden resource in a way that is conducive to creating ecological conditions that will foster the stability and habitability of the site. Creating microtopographical features on the waste rock storage facility, such as mounds and swales, may work to stabilize the site by reducing erosion potential, controlling sediment transport (Schor and Gray 2007), and influencing seedling growth and survivability (Biederman 2010). Ecologically habitable conditions may be achieved on a waste rock storage facility by creating mounds and swale features that provide a variety of microsites differing by aspect, growing medium depth, nutrient concentrations (El-Bana et al. 2003; Bruland and Richardson 2005), and moisture (Bledsoe and Shear 2000; Löf et al. 2006). This research focused on measuring the hydrologic, edaphic, and vegetative responses to the microtopographical conditions created by the formation of mounds and swales on the waste rock storage facility of a former metal mine. The underlying monitoring strategies applied in the study may also be used to assess the success of a large-scale reclamation program.

Research Summary

Near Surface Overburden Physical Conditions Respond To Mounding.

Mounding had a significant effect on near surface overburden moisture. Bottom swales had significantly higher near surface moisture than all other mound locations. The distinct gradient of average overburden moisture measured in 2010 increased from the top mound to the slope-downhill, slope-uphill and bottom swale topographical mound locations, in that order. Mounding had no measured effect on near surface overburden temperature.

Overburden Nutrient Availability Is Influenced By Mounding.

The created microtopography significantly affected the concentration of some nutrients, resulting in higher levels in the bottom swales likely due to nutrient leaching and displacement from locations on the mound. Whereas, there was significantly less organic matter measured in the bottom swales compared to locations on the mounds.

Overall Plant Survival Rates Were High.

Total lupine seedling survival after 5 years was 81%, which is much higher than values observed in previous works that studied survival rates of planted lupine seeds, with survival rates ranging from 6-50% after one year (Bowles et al. 1997, Pavlovic and Grundel 2008). Overall willow plug survival rates (97%) measured in this study after 5 years since planting also demonstrated a very high benchmark for seedling success. This assertion is supported by previous findings, such as in the planting program in the Elkview Operations in Sparwood BC, which demonstrated a willow seedling survival of 80-90% 3 years after planting on a waste rock storage facility (Przeczek and Amos 2014). The higher survival rates measured in this study may be attributed to the enriched local conditions provided by the commercial growing medium used in the plugs of this study, compounded by the advanced root system within the nursery-grown plugs.

Plant Survival And Growth Are Influenced By Mounding.

This study found differences in plant survival and growth, resulting at least in part from the differences in overburden physical habitat occurring due to the microtopography formed by the surface preparation technique of mounding.

Lupine survival, cover and biomass were significantly lower in plants occurring in the bottom swales in comparison to the other topographical mound positions, which is consistent with the findings in similar studies on nitrogen-fixing species. In addition, *Rhizobium* nodule formation on lupine roots was significantly suppressed in the bottom swales in comparison to other microtopographical mound positions. The significantly higher levels of sodium and potassium ions measured in the bottom swales in this study suggest that salt stress may have distorted lupine *Rhizobium* nodule formation, at least in the first year of growth.

After the second year of growth, willows planted in the bottom swales had significantly higher cover in comparison to the other locations on the mounds, which is expected with the rapid growth rate and high tolerance to for saturated soils demonstrated by *Salix* species. However, this is contrary to observations after the first year of growth where willows planted in the bottom swales experienced the lowest survival, lowest cover, and shortest root length in comparison to willows planted on the other mound locations.

Management Implications for Mine Reclamation

Hydrologic Implications

Overburden moisture content in a sloped metal mine waste rock storage facility is a fluctuating parameter that can be influenced by the dump's surficial microtopography. Understanding how microtopographical features, such as mounds, can be applied as a form of surface preparation in mine reclamation to provide distinct habitat conditions and accommodate different moisture requirements for a variety of plant functional groups can assist land managers select appropriate plant species and prescribe the most suitable planting location to optimize their growth. For example, mounding may be used in reclamation programs to facilitate the ingress of drought-tolerant plant species on the mounds and flood-tolerant wetland species in the bottom swales (Hough-Snee et al.

2011). Furthermore, the variety of hydrological conditions provided by the mounds and swales has a greater chance of achieving conditions favourable for native seedling emergence and survival in comparison to sites with homogenous microtopography (Barry et al. 1996).

Edaphic Implications

Despite the lowest levels of organic matter measured in the bottom swales and the slight decrease in organic matter observed in the bottom swales after 5 years, it is expected that organic matter will accumulate more rapidly in the bottom swales than the other treatments due to the elevated moisture levels occurring in the bottom swales that, over time, may inhibit aerobic decomposition of litter (Bruland and Richardson 2005). Building soil organic matter is usually a management goal for agricultural land managers and it is also favorable in the context of mine reclamation. Increases in organic matter may improve other overburden physical properties such as ability to aggregate and control erosion, as well as buffer pH (Ponnamperuma 1984).

In general, overburden at mine sites tends to be found deficient in essential plant nutrients such as nitrogen, phosphorus, and potassium (Sheoran et al. 2008; Sheoran et al. 2010), which is consistent with the nutrients measured in the overburden in this study. It is important for reclamation managers to identify any deficiencies in the growing medium, prior to its application in reclamation to ensure that suitable amendments are considered, and if required, applied to the growing medium while it is stockpiled. Specific fertilizers should be prescribed based on the characterization of the overburden. Mounding may help prevent the complete wash-out of fertilizer granules applied after overburden placement and surface preparation, however, the granules would be more likely to accumulate in the bottom swales. Therefore, a delayed-release fertilizer may be the best option for fertilizing mounds and swales.

The properties of overburden vary at different mine sites and are influenced by the resource being mined and the geology of the area mined. For example, it is not uncommon to find elevated metal levels in the overburden of a metal mine, such as the elevated vanadium, arsenic and copper concentrations measured in the overburden of this study. Prior to salvaging soil, reclamation managers should characterize representative soil units slated for salvage for their suitability as a growing medium for reclamation. Soils deemed suitable for salvage should be sampled to determine their local metal concentrations. If metal levels exceed the limits identified in the Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health (CCME 2007), or exceed the Soil Criteria for Toxicity to Soil Invertebrates and Plants outlined in the Contaminated Sites Regulation (375/1966), then the soil with elevated metals should not be considered for use as a growing medium and should be stored separately.

Despite pre-placement overburden characterization, it is possible for heavy metals to accumulate in certain ‘hot spots’ after final placement. For example, baseline overburden characterization did not detect exceedances in arsenic nor vanadium. However, the microtopographical features established at the Kemess Mine site during reclamation provided a gradient of edaphic conditions in the overburden that was applied as a growing medium on the former metal mine’s waste rock storage facility. The difference in soil chemistry occurring on the mounds and in the swales is likely the result of the accumulation of nutrients and metals leaching to the bottom swales displaced from the tops and slopes of mounds. It is important to recognize that metallic micronutrients may be more bioavailable in the bottom swales, which could result in toxicity to some plants growing in the bottom swales (Barcelo and Poshenrieder 2003). Revegetation of microtopographical features with elevated metal concentrations can be managed to effectively avoid metal toxicity in plants and associated uptake by animals, by identifying metal-tolerant plant species that are unpalatable to local wildlife, which would be suitable for planting in the bottom swales. Examples of species considered unpalatable to local wildlife, which should be further investigated include *Achillea millefolium*, *Leymus innovatus* and some *Carex* species (Burton and Burton 2003).

The chemical gradient induced by created microtopography may also result in negative consequences to establishing microbial communities. For example, the accumulation of some available ions (sodium and potassium) in the bottom swales may induce a salt stress on *Rhizobium* root nodules, resulting in the complete suppression of nodule formation in some roots growing in the bottom swales. Determining the habitat requirements of plant functional groups, such as nitrogen-fixing species, prescribed for application in reclamation will be essential to ensure they are planted in locations that will maximize their survivability and ability to fix nitrogen and supply this critical resource to colonizing plants.

Vegetation Implications

A waste rock storage facility presents an ideal site for plant recovery and succession research, in that it is a relatively large site, void of vegetation and propagules (Wiegleb and Felinks 2001). A simple conceptualization of the relationship between a reclamation site such as a waste rock storage facility and a recovered ecosystem is that the emerging ecosystem exists on a trajectory toward a desired ecological endpoint, all occurring along a gradient of alteration (Miller and Bestelmeyer 2016). This philosophy draws on Clement's successional theory, considering early colonizing species to be deterministic with the expectation that species composition will converge to a steady climax following a sequential linear process (Clements 1916). The conceptual ecological endpoint for the waste rock storage facility at Kemess South may include species consistent with the Moist Cool Spruce-Willow-Birch (SWBmk) Site Series-02 (Delong 2004), which was identified in nearby areas (Evans 2016). This community is composed of up to 10% trees, 35% shrubs, 40% herbs, and 50% mosses, including but not limited to the following (Delong 2004):

- *Picea glauca* (white spruce)
- *Pinus contorta* (lodgepole pine)
- *Salix* spp. (willows)
- *Juniperus communis* (common juniper)
- *Betula nana* (scrub birch)
- *Abies lasiocarpa* (subalpine fir)
- *Linnaea borealis* (twinflower)
- *Anemone parviflora* (northern anemone)
- *Festuca altaica* (Altai fescue)
- *Lupinus arcticus* (arctic lupine)
- *Hylocomium splendens* (step moss)
- *Cladina spp*. (reindeer lichens)
- *Pleurozium schreberi* (red-stemmed feathermoss)
- *Peltigera aphthosa*

Most reclamation management strategies aim to facilitate the rapid onset of successional processes, or to maintain a desired community at a particular successional sequence because it has elements of value (Miller and Bestelmeyer 2016). Severely disturbed sites require direct intervention to enhance ecologically habitable conditions and to initiate the ecosystem repair process (Rietkerk et al. 1997). Without direct intervention by reclamation managers, plant establishment and growth is often not satisfactory in the context of reclamation success (Walker and del Moral 2003).

Knowing the life history of select reclamation species including their response to habitat conditions occurring within the reclamation site will assist in assembling communities and accelerating ecosystem recovery processes (Walker and del Moral 2003). The vegetation patterns resulting from and correlated to microsite conditions may be used to build knowledge and predict changes in biotic expression at similar sites (Wiegleb and Felinks 2001). The results of similar studies relating vegetation patterns to measurable environmental factors can be used to adaptively manage the reclamation approach and increase the effectiveness of restoration activities (Walker and del Moral 2003).

The path to ecosystem recovery is determined by the abiotic and biotic resources present to initiate the repair process. The role of a reclamation manager is to introduce the resources that facilitate ecosystem recovery. From a reclamation management perspective, the goal is to facilitate the introduction of soil (overburden) and vegetation to the disturbed site relatively quickly (Wiegleb and Felinks 2001). Revegetation challenges experienced in mine reclamation include dispersal limitations (Eriksson and Ehrlen 1992, Walker and del Moral 2003) and diminished soil conditions (Sheoran et al. 2010) which can be overcome by direct introduction of propagules. Planting commercially propagated plugs appears to be a successful technique for reclamation managers who wish to rapidly revegetate a drastically disturbed area. Owing in part to the advanced root system developed within the plugs along with the enriched local conditions associated with the commercial growing medium used in the plugs, the overall survival of seedlings planted in this study was very high.

If the method of planting had been by directly sowing seeds on the waste rock storage facility, it is unlikely that the results of these studies would have been similar. This assertion is supported by the germination test plots conducted on the Kemess waste rock storage facility in 2011, which observed germination rates of less than 10% for six native plant species after one growing season (Appendix C). For large scale reclamation programs, reclamation managers must assess the feasibility of using commercially propagated native seed for transplanting onto the disturbed site in comparison to direct seeding the site with native seed. There are high costs associated with both techniques, and depending on the timeline, the levels of success will vary.

Environmental factors such as microtopography and microclimate influence the uniformity of plant communities, affecting seedling survival and growth. Plant survival and growth are influenced by microsite conditions created by mounding. Firstly, lupine growth and survival was found to be lower in the bottom swales in comparison to all other treatments, indicating that nitrogen-fixing species may be sensitive to the increased resource retention, such as water and nutrients, in the bottom swales. Therefore, future planting programs should avoid planting nitrogen-fixing species such as lupine in bottom swales. Secondly, microtopographic features, at least initially, did influence the survival and growth of willow species. Willows planted in the bottom swales had the lowest survival rate and shortest roots when measured in the second growing season, despite having measured significantly higher cover in the bottom swale than did locations on the mound. Rapid growth rate and high tolerance for saturated soils is demonstrated by many *Salix* species (Kuzovkina and Volk 2009) and consistent with results of a similar study on wetland species (Bruland and Richardson 2005). It is important to note that overall willow survival in the study was very high, with over 97% of seedlings surviving after 5 years. Therefore, *Salix prolixa* should be classified as highly versatile and should be considered for application in various mine reclamation programs where it grows.

Suggested Future Studies

Creating ecologically habitable conditions on the waste rock storage facility of a former copper mine is a complex process, and developing strategies for measuring and communicating ecological responses to the reclamation conditions created is a difficult but essential task to effectively assess the success of any large-scale reclamation program

(Dale and Beyeler 2001, Schiller et al. 2001, Lausch and Herzog 2002, Niemi and McDonald 2004, Ruiz-Jaen and Aide 2005). Further research that can be pursued to augment the findings of this research and to support assessments of reclamation success include:

- Future studies can examine how the effects of mounding persist over longer periods of time. This can include monitoring:
    - the structure of vegetation that naturally colonizes the mound treatments, including parameters such as plant cover, density, biomass, and height.
    - ecological processes by measuring biological interactions such as quantifying *Rhizobium* populations in legume roots over longer timeframes to confirm and further clarify the effects of mounding.
- Future studies that look at effects of mounding on species diversity as a measure of richness and abundance of organisms within different trophic levels (Nichols and Nichols 2003, Weiermans and van Aarde 2003). For example, a study can survey overburden microarthropod communities occurring in each microtopographical mound position, unmounded sites, and natural sites. Microarthropod density and community structure occurring in reclaimed areas may be used as an indicator of a functioning ecosystem (Schaefer and Hocking 2015) and as a measure of ecosystem resilience (Peterson et al. 1998).
- Plant tissue analysis should be conducted for heavy metals with elevated concentrations such as arsenic, and copper (and molybdenum), to identify any concerns for potential levels of phytotoxicity and critical levels of animal ingestion. Elevated concentrations of heavy metals in overburden can negatively influence plant growth by inhibiting critical plant metabolic functions, potentially resulting in plant mortality (Garbisu and Alkorta 2001, Schmidt 2003, Schwartz et al. 2003). Identifying plant species and their abilities to hyperaccumulate heavy metals will help determine their role in revegetating a mine site with elevated concentrations of heavy metals.
- A field study that looks at direct seeding of native species of various functional groups on the mounding treatments, to examine the effects of mounding and created microsites on seed germination and overall seedling survival. This will

provide insight into the feasibility of direct seeding native species in comparison to planting commercially propagated seedlings.

Conclusion

Mounding is a technique commonly used in the restoration of forests, grasslands, wetlands, and landfills. This study highlights that mounds can also be applied in a mine reclamation setting, particularly in reclamation works of metal mines in northern BC, but likely can be applied at most metal mines. The concave-convex slope features induced by mounding provide a variety of physical, chemical, and biological conditions conducive to the habitability of a variety of plant functional groups. The reclamation of waste rock storage facilities can be managed to facilitate opportunities for the differentiation of plant species composition to occur at the microtopographic level because of the distinct habitat conditions induced by mounding. The application of mounds, therefore, is a technique that reclamation managers can use to manipulate the biophysical growing medium conditions to facilitate the introduction of living organisms that perform ecosystem recovery. When managing an emerging ecosystem, it is important to recognize that the recovering ecosystem exists along a path of alteration, whereby the desired future state occurs along a similar path that is inherently dynamic in nature and not frozen in time (Miller and Bestelmeyer 2016).

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APPENDIX A LUPINE SEED EVALUATION

Annual collection dates range from mid-July to end of August. Individual pod readiness varies on each stalk. However, as a general guideline, as soon as some of the pods on the seed stock have turned grey, the entire stock can be harvested. The rest of the pods will mature in the collection sacs when placed under heat lights. Be careful not to clip the pod stocks too early as the seeds will not have time to ripen.

After the pods have ripened, they should readily pop open. If pods remain enclosed in the sacs, the seed is easier to contain. Without interference, the natural trajectory of lupine seeds covers quite a distance. After the pods have successfully opened, the sacs can be emptied and the seed separated from the rest of the debris. As the pods are usually picked at varying stages of maturity, the seeds will also vary in readiness. Figures 1-5 show the range in seed readiness classes.

Figure 1. Class 1; Dark, 4-5mm long
Rule divisions are 1.0 mm.

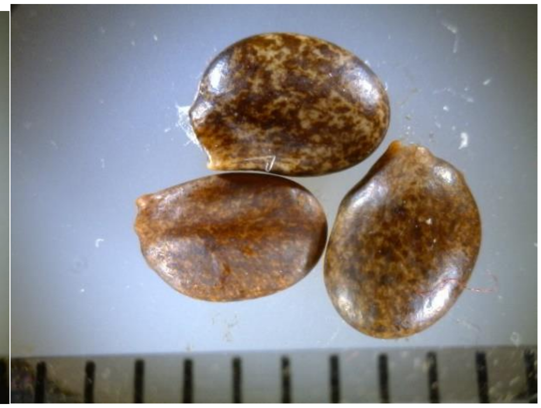

Figure 2. Class 2; Brown, 3-4 mm long

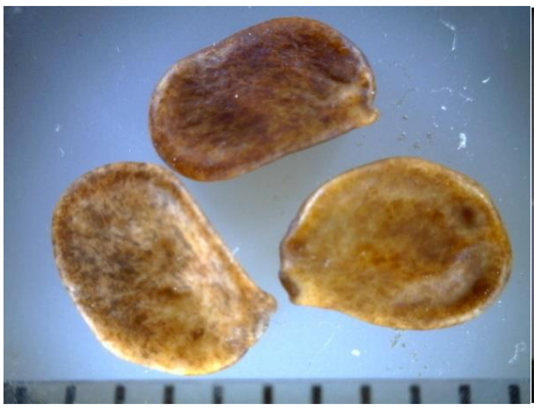

Figure 3. Class 3; Light brown, flattened
Rule divisions are 1.0 mm.

Figure 4. Class 4; Green, flattened

Figure 5. Classes 1, 2, 3, 4 Lupine seed

There are often insects and diseases present in lupine pods. Generally, if a ripened pod readily pops open, infestation is not a concern. However, if the pod does not pop open naturally, a visual inspection of the interior of the pod usually finds evidence of lupine seed miners as seen in Figure 6. As a result of infestation, the interior of the lupine seed is mined and becomes no longer viable. Figure 7 illustrates mined lupine seed that is no longer viable. In most cases of harvesting, it is not worth it to manually open the pods that do not open naturally.

Figure 6. Lupine seed miners

Figure 7. Mined lupine seeds

Harvested seed must be sorted to minimize the amount of non-viable seed passed on to the nursery. Class 4 seed should be removed as well as any seed miners present as seen in Figure 8.

Figure 8. Viable seed, non-viable seed, seed miners.

APPENDIX B EFFECTS OF MICROTOPOGRAPHY ON NEAR SURFACE AIR TEMPERATURE AND LIGHT INTENSITY

Introduction and study objectives

The created microtopography on the waste rock storage facility of a former metal mine may facilitate differences in near surface air temperature and light intensity. The objective of this study is to determine whether differences in microtopography affect near surface air temperature and light intensity during the summer and fall periods. Specific objectives of the study are to:

- Quantify effects of microtopography on near surface air temperature
- Quantify effects of microtopography on surface light intensity

Materials and Methods

Four treatments on each aspect were instrumented with a sensor that measures near surface air temperature and light. HOBO Pendant Temperature/Light data logger sensors were positioned in the center of one plot for the bottom swale, top mound, slope-downhill, and slope-uphill locations on the northwest and southwest slopes, for a total of 8 sensors. Data for near surface air temperature, and light were recorded in 1 minute intervals for each sensor for the duration of the study. Summer data was collected from June 20 to July 10 and fall data was collected from September 27 to October 17 2015. Data loggers were downloaded after each time period.

Data were analyzed with SPSS 23 (SPSS, Inc., Chicago, IL, USA). Data were classified into four treatments: bottom swale (n = 2), slope-downhill (n = 2), slope uphill (n = 2) and top mound (n = 2) levels of topographical positions on the mounds. Differences in datasets among microtopographical positions were examined using one-way ANOVA with blocking followed by Tukey's HSD when the ANOVA indicated a significant F-Value. Dependent variables were tested for assumptions of normality using the Shapiro-Wilk test for normality and a Levene's test for homogeneity of variances in SPSS. If required. data transformations were conducted to better conform to the assumptions of an ANOVA.

For purposes of presentation and ease of interpretation, the statistical analysis on the transformed data are reported but the data in the paper (text and figures) is presented in their original units.

Results

Maximum daily near surface air temperature in summer 2015 was statistically significantly different between different treatments. The difference in the summer of 2015 was attributable to differences in near surface air temperature on the slope-downhill compared to all other topographical positions ($p<0.001$). There were no other differences found between near surface maximum, minimum, and average air temperatures among treatments in 2015. There was a significant blocking effect for maximum summer near surface air temperature ($p=0.009$).

Summer air temperature summary graphs are presented in Figures 1,2,3. Fall air temperature summary graphs are presented in Figures 4, 5, 6.

Average daily near surface light in summer 2015 was statistically significantly different between different treatments. The differences in the summer of 2015 were attributable to differences in near surface light on the top mounds compared to all other topographical positions ($p<0.001$). Maximum daily near surface light in summer 2015 was statistically significantly different between different treatments. The differences in the summer of 2015 were attributable to differences in near surface light on the top mounds compared to the slope downhill ($p=0.05$). Average daily near surface light in fall 2015 were statistically significantly different between different treatments. The differences in the fall of 2015 were attributable to differences in near surface light on the top mounds compared to the bottom swale ($p=0.049$). There was a significant blocking effect for maximum summer light ($p=0.002$).

Summer light summary graphs are presented in Figures 7,8. Fall light summary graphs are presented in Figures 9, 10.

The data collected in this study are specific to the geographic location of the study area and to the climatic conditions experienced during the timeframe of the study.

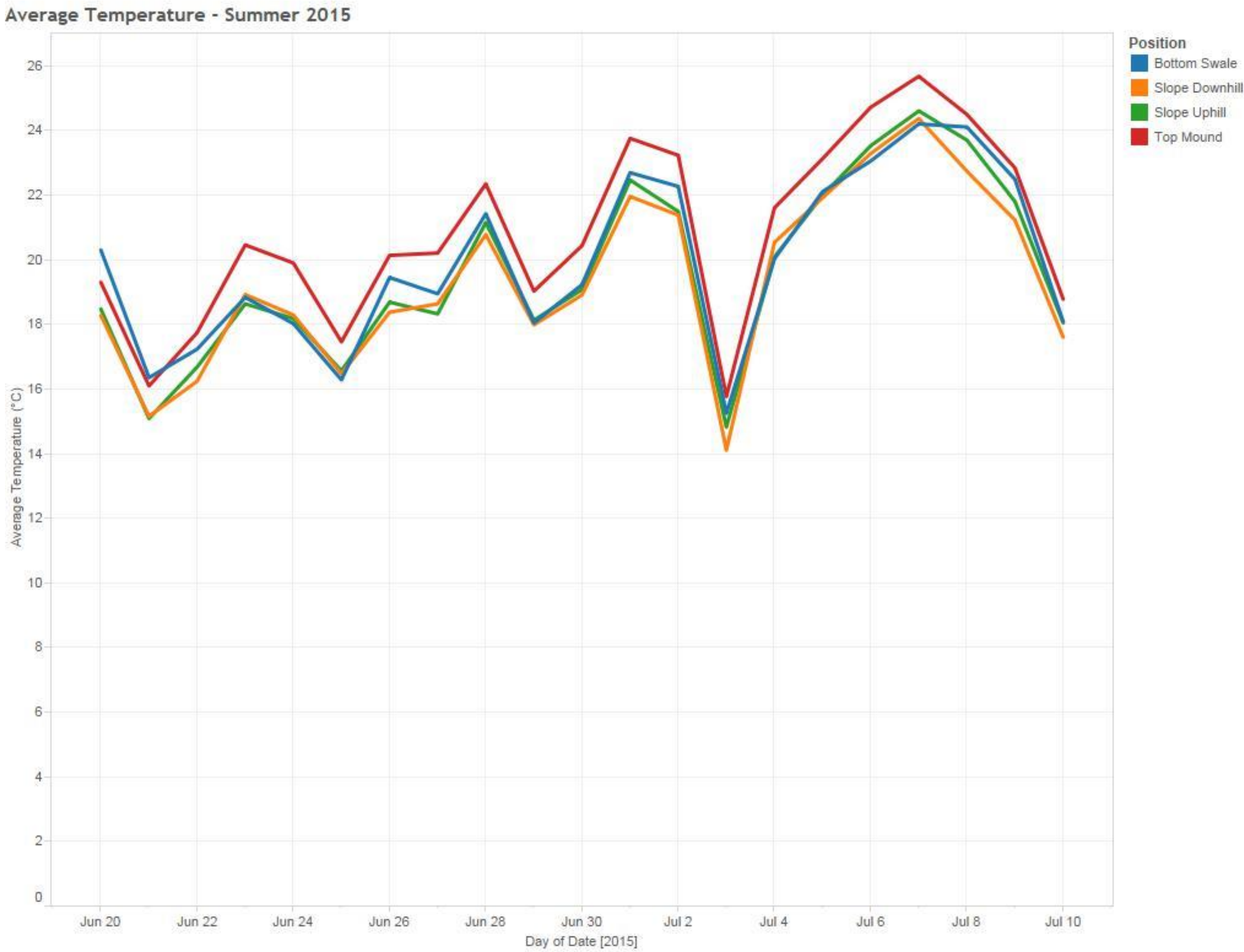

Figure 1: Average daily near surface air temperature (°C), June 20-July 10 2015 (n=8). Letters indicate significant differences between means (Tukey HSD) at α=0.05.

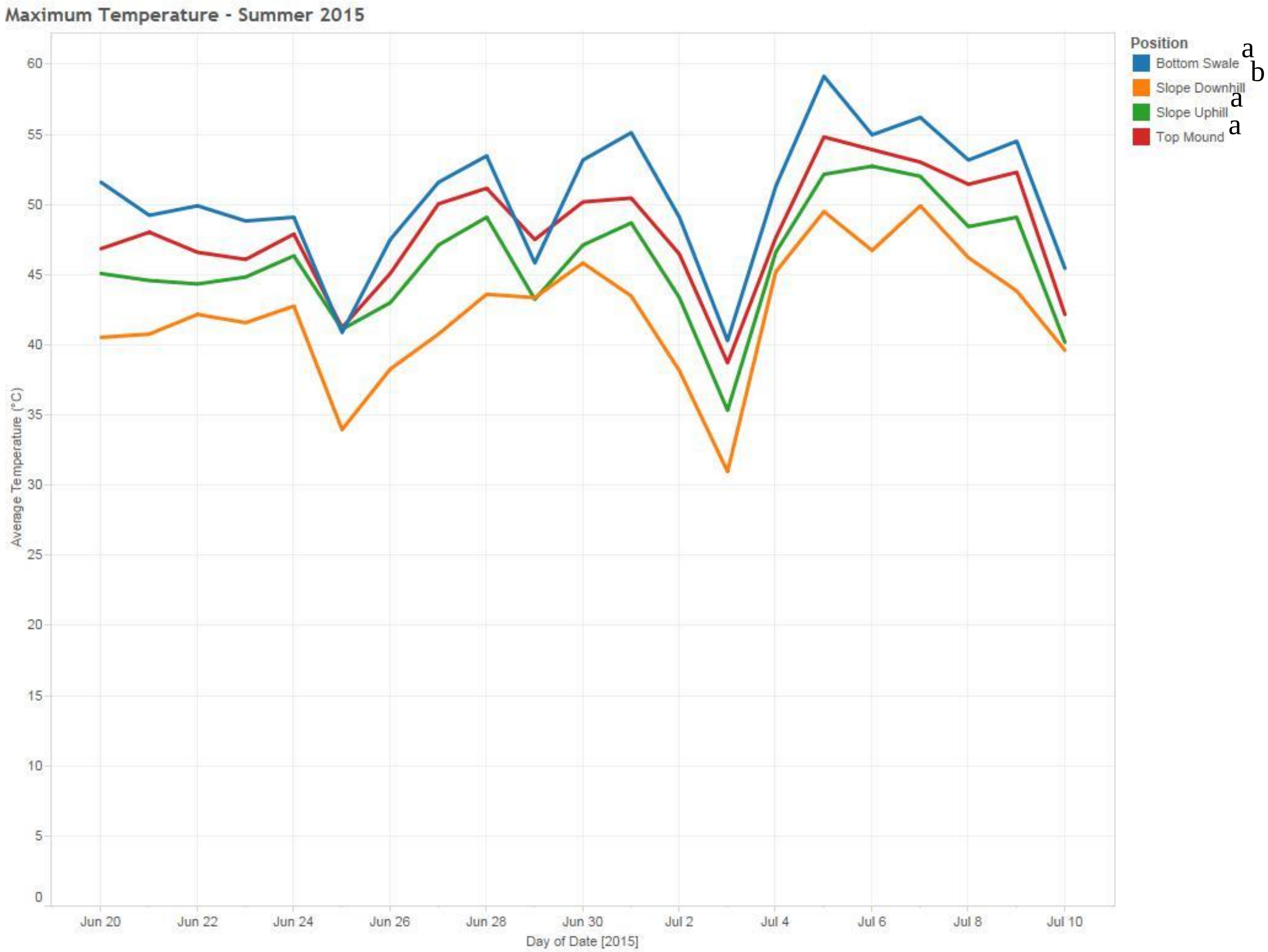

Figure 2: Maximum daily near surface air temperature (°C), June 20-July 10 2015 (n=8). Letters indicate significant differences between means (Tukey HSD) at α=0.05.

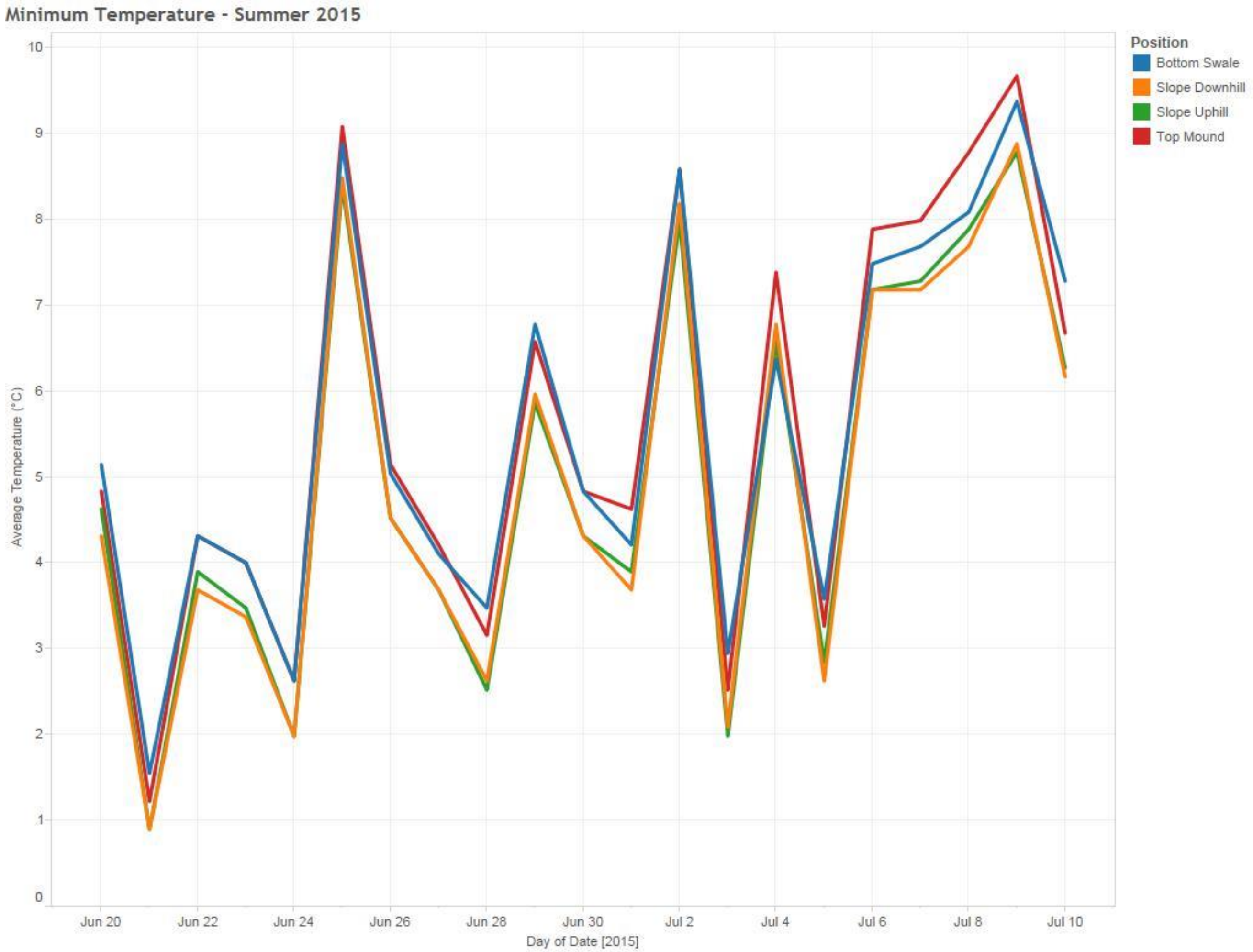

Figure 3: Minimum daily near surface air temperature (°C), June 20-July 10 2015 (n=8). Letters indicate significant differences between means (Tukey HSD) at α=0.05.

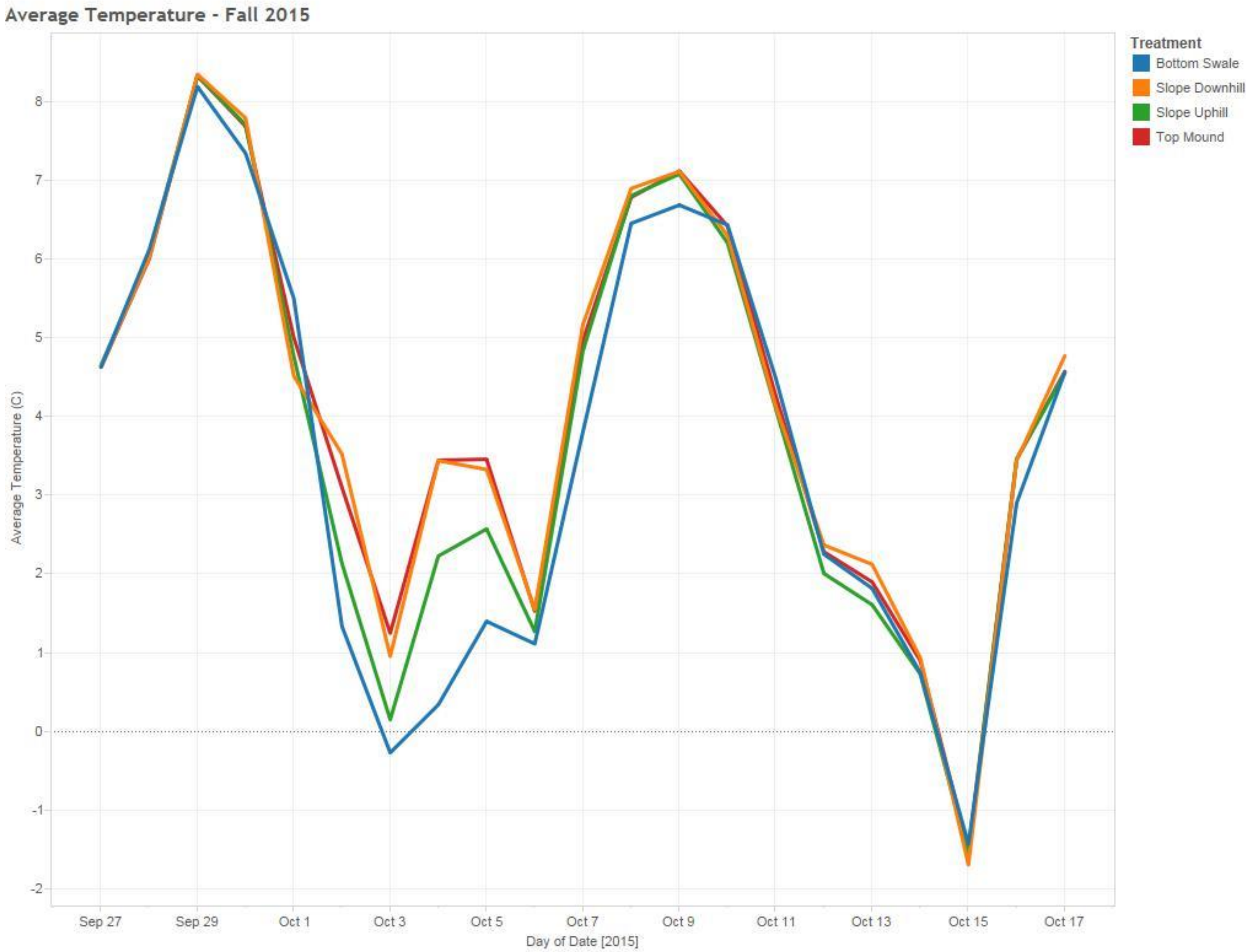

Figure 4: Average daily near surface air temperature (°C), September 27-October 17 2015 (n=8). Letters indicate significant differences between means (Tukey HSD) at α=0.05.

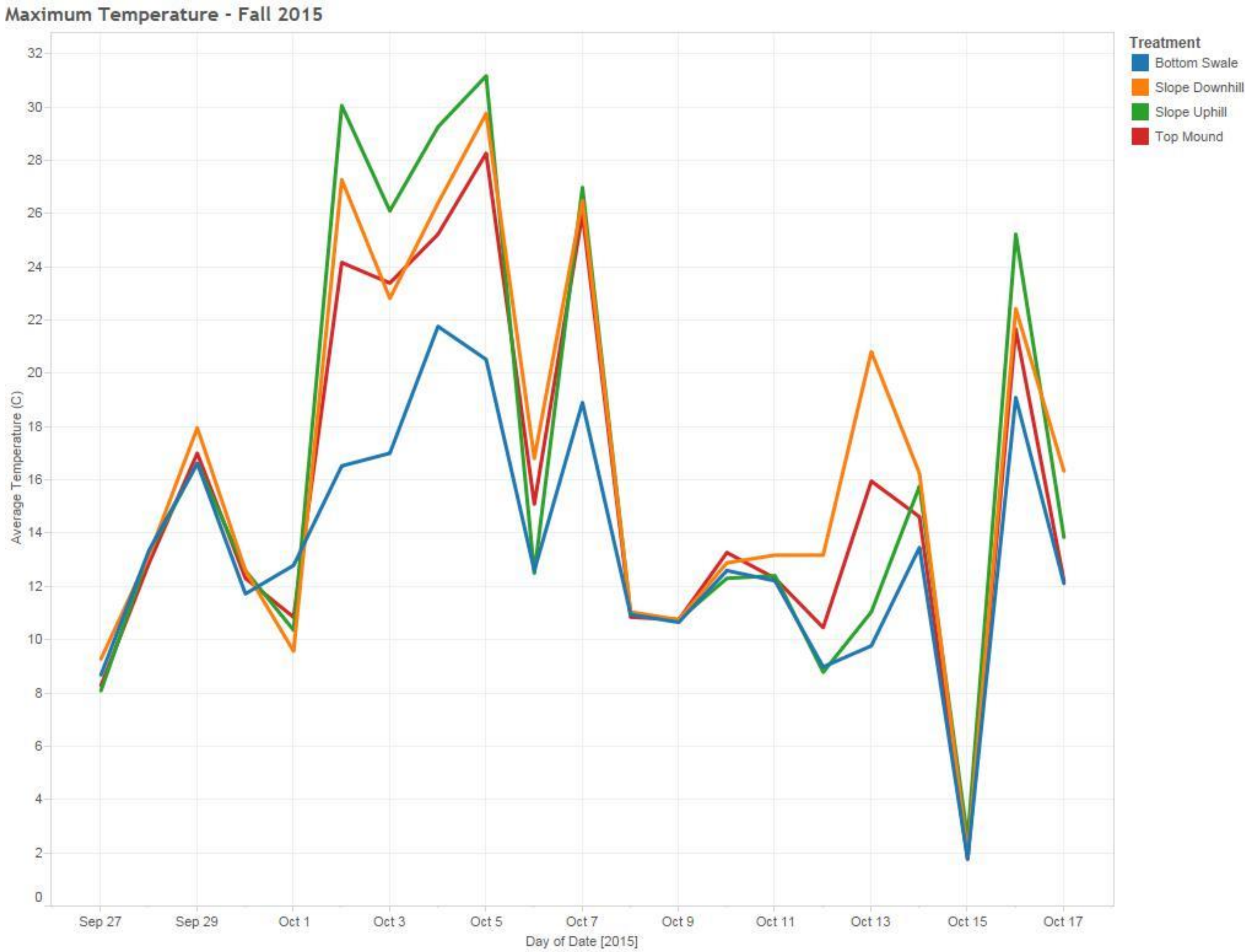

Figure 5: Maximum daily near surface air temperature (°C), September 27-October 17 2015 (n=8). Letters indicate significant differences between means (Tukey HSD) at α=0.05.

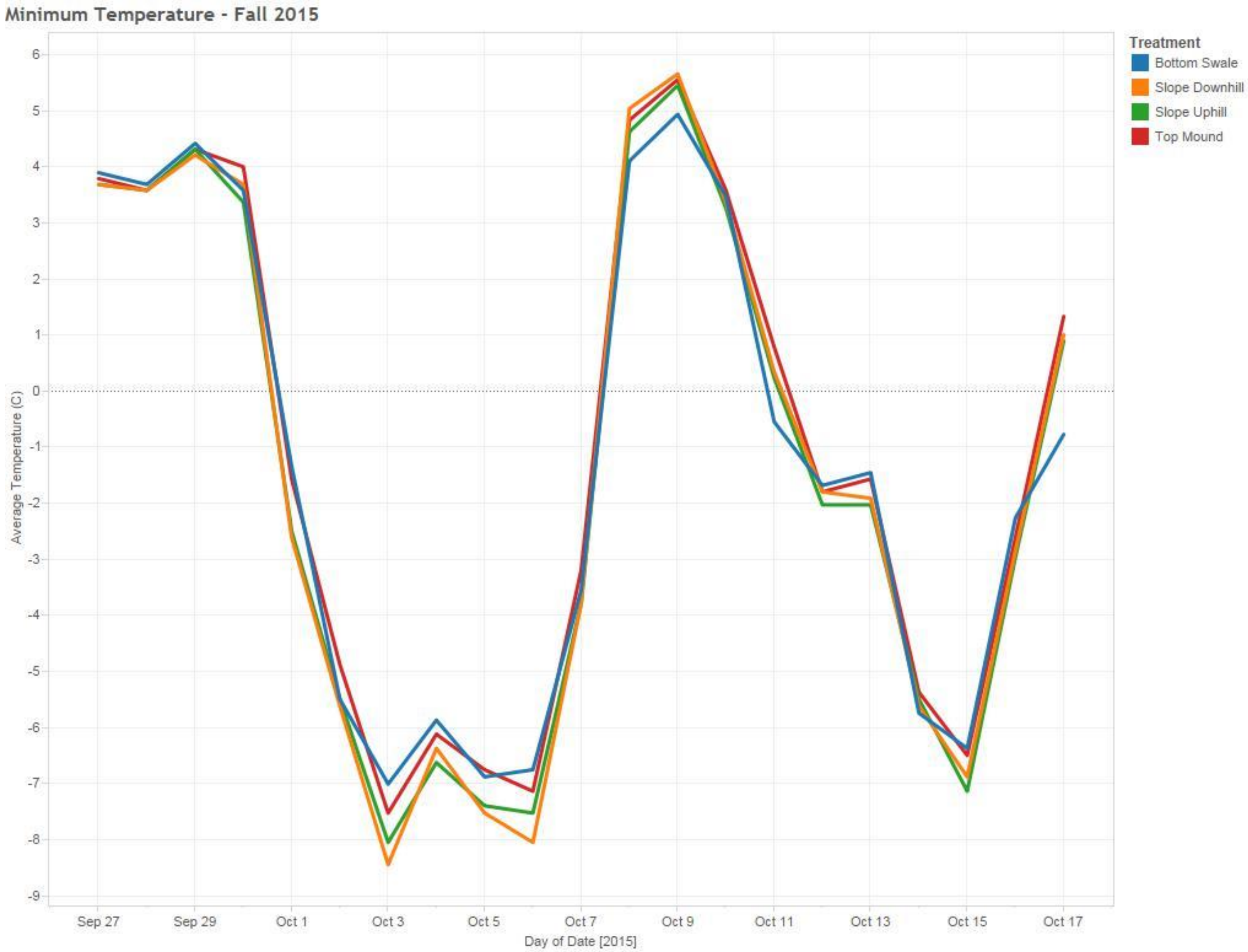

Figure 6: Minimum daily near surface air temperature (°C), September 27-October 17 2015 (n=8). Letters indicate significant differences between means (Tukey HSD) at α=0.05.

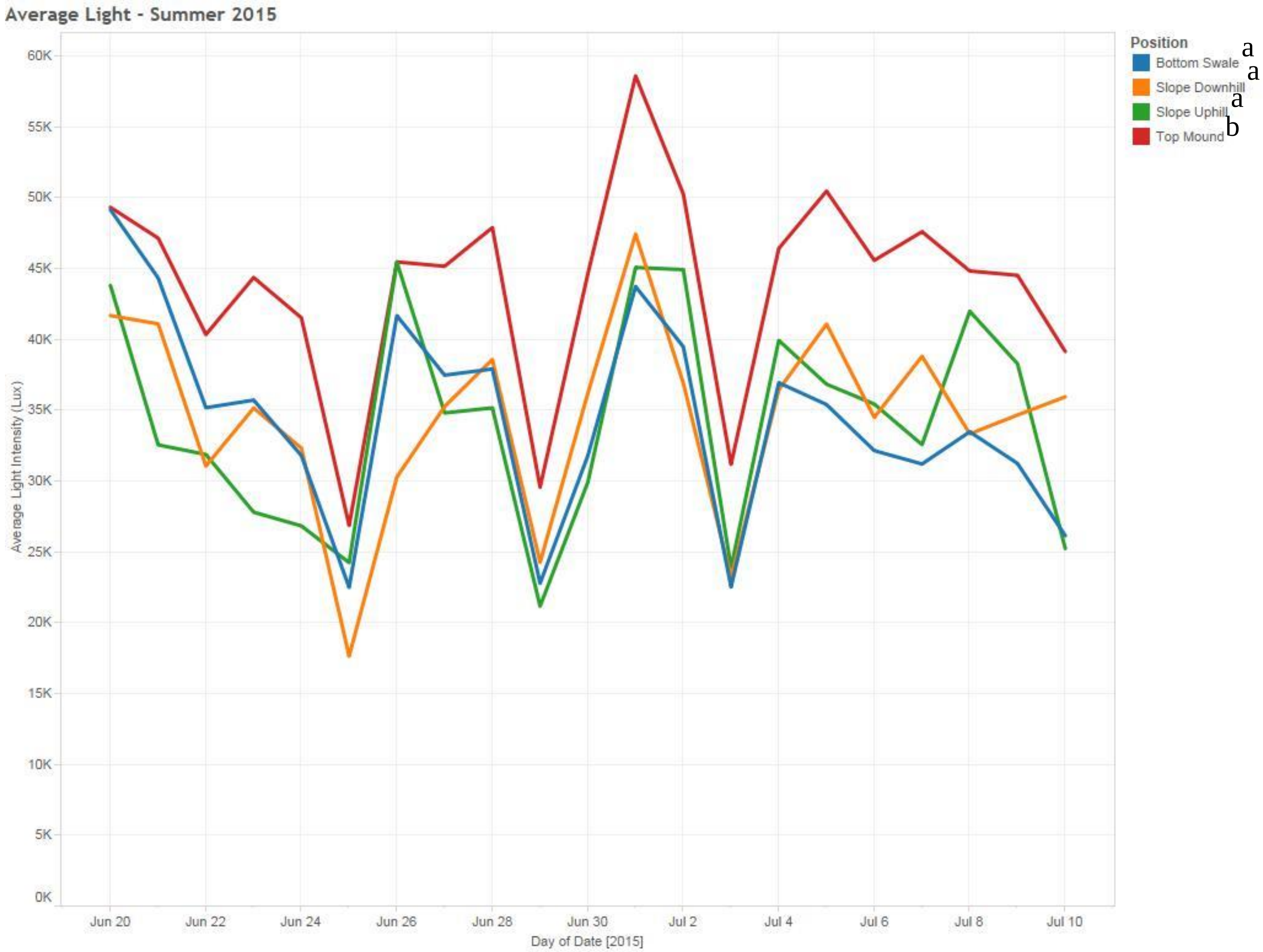

Figure 7: Average daily light intensity (Lux), June 20-July 10 2015 (n=8). Letters indicate significant differences between means (Tukey HSD) at α=0.05.

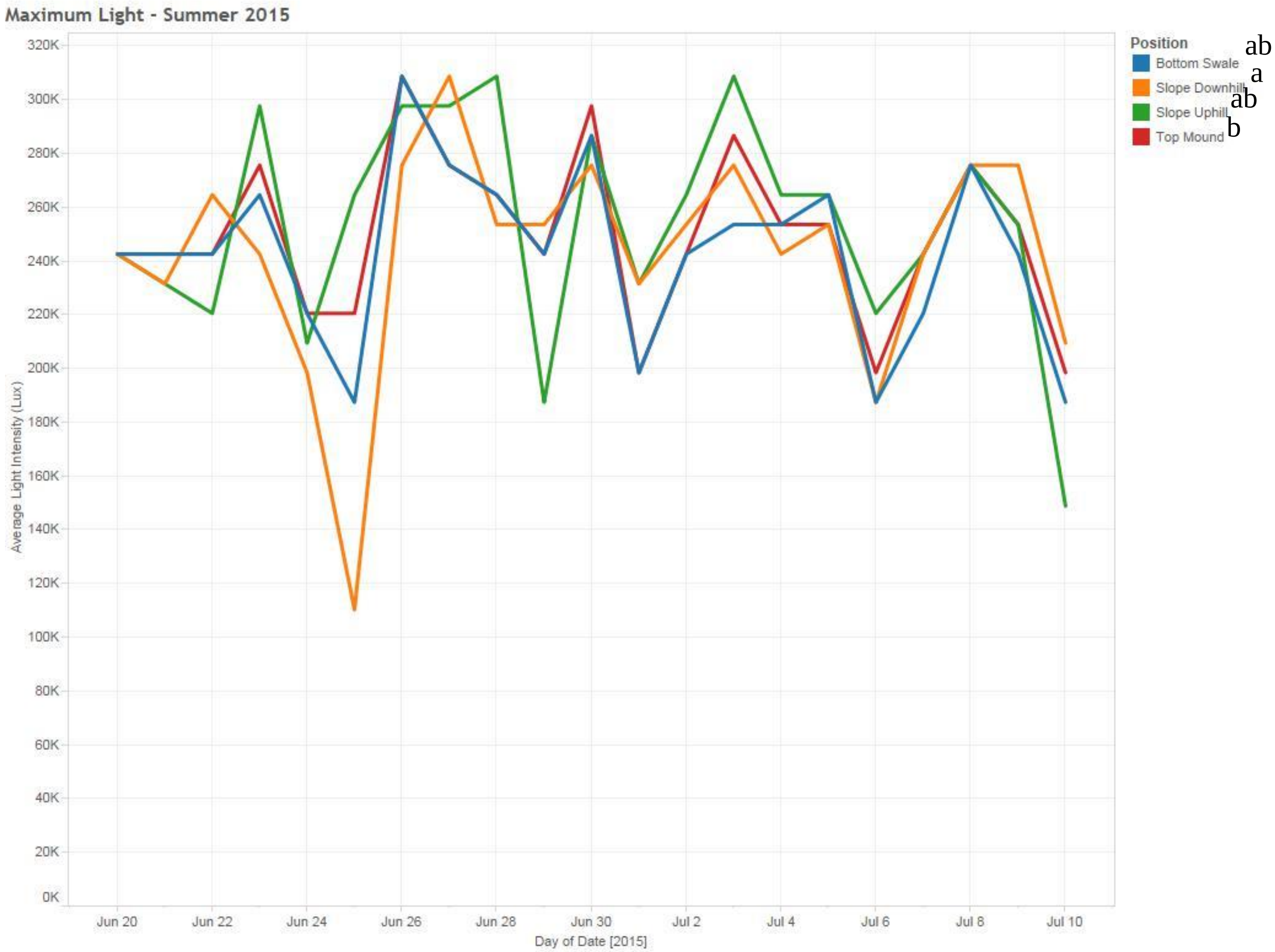

Figure 8: Maximum daily light intensity (Lux), June 20-July 10 2015 (n=8). Letters indicate significant differences between means (Tukey HSD) at α=0.05.

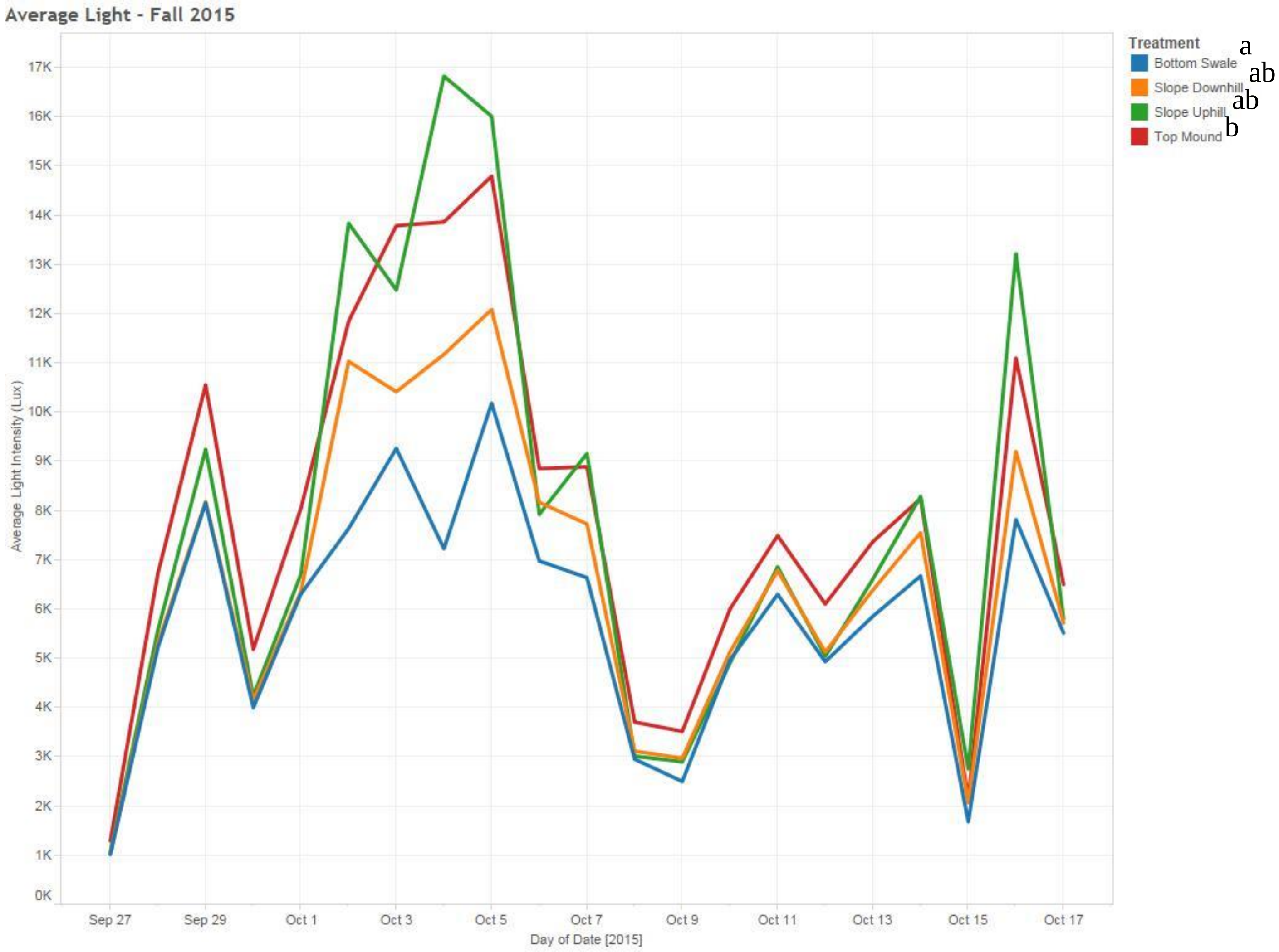

Figure 9: Average daily light intensity (Lux), September 27-October 17 2015 (n=8). Letters indicate significant differences between means (Tukey HSD) at α=0.05.

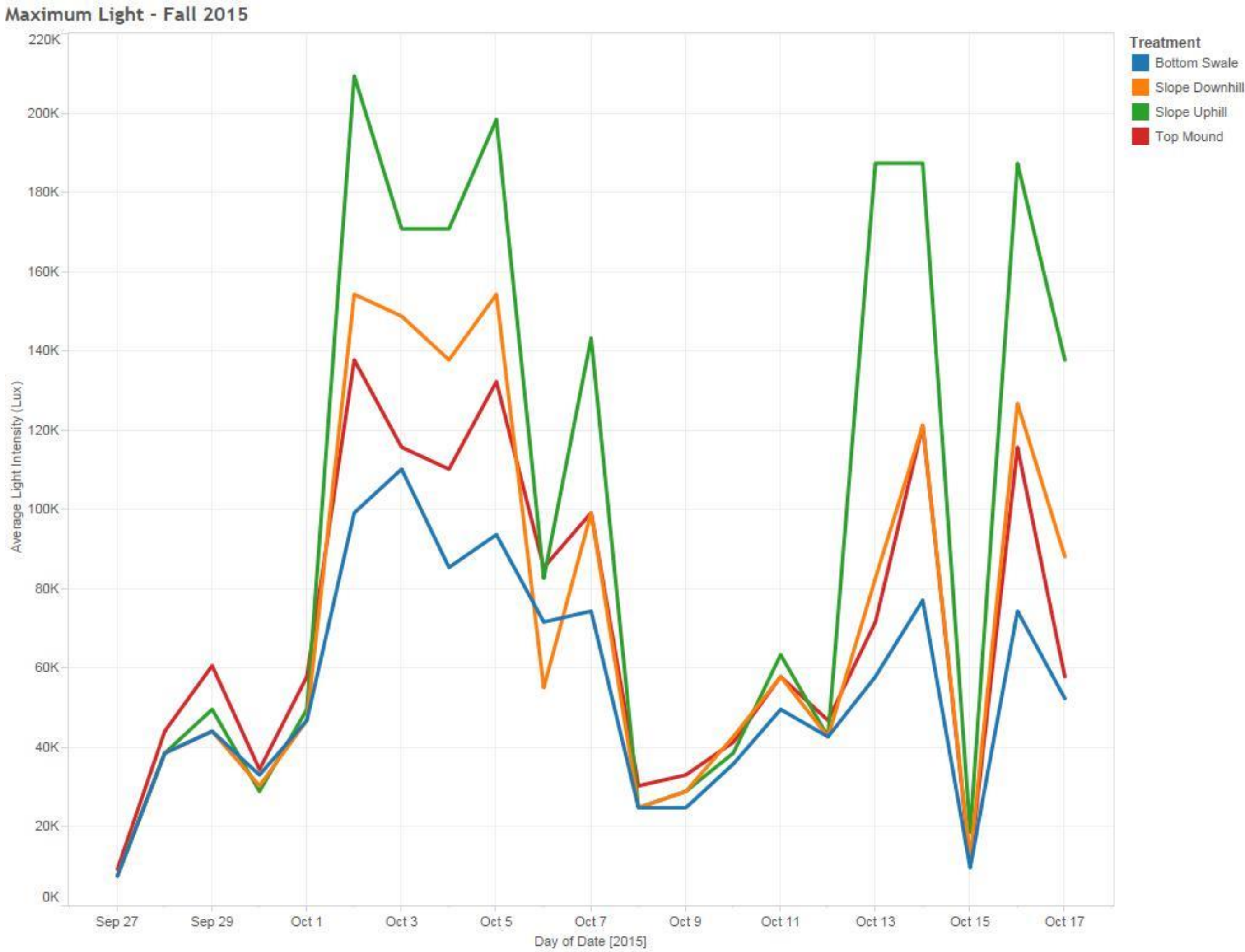

Figure 10: Average daily light intensity (Lux), September 27-October 17 2015 (n=8). Letters indicate significant differences between means (Tukey HSD) at α=0.05.

Conclusion

The created microtopography on the waste rock storage facility of a former metal mine facilitated significant differences in near surface air temperature and light intensity. The differences in near surface air temperature were significant during the period studied in the summer, which was attributable to the slope downhill treatment reaching significantly lower daily maximum temperatures compared to all other treatments. Average daily light intensity measured at the surface was significantly different among treatments in the summer and fall periods, with the top mound achieving the highest average daily light intensity levels. Maximum daily light intensity measured at the surface was significantly different among treatments in the summer period, attributable to the top mound being different from the slope downhill treatment.

APPENDIX C – GERMINATION TEST PLOT

Introduction

This study was conducted to evaluate the germination of seeds of six native plant species on the waste rock storage facility of a former metal mine. The results of the study will be used to inform future reclamation planning and specifically to help determine which species, if any, are suitable for future seeding programs on the waste rock deposit.

Methods

Seeds from all species were collected from the Kemess Mine site during 2010. All seeds underwent a 5-month cold stratification. Germination test plots were established at the top of the lower bench on the northwest side of Kemess Mine's waste rock storage facility. The study area was broken down into a grid of 35 individual plots measuring 1m x 1m, with a half meter between plots. There were 7 treatments consisting of 100 seeds each with 5 replicates of each:

1. Control – No seeds
2. *Lupinus arcticus* – Arctic Lupine
3. *Mertensia paniculata* - Tall Bluebell
4. *Astragalus alpinus* - Alpine Milkvetch
5. *Carex macloviana* – Thickhead Sedge
6. *Arnica cordifolia* – Heart-leaf Arnica
7. *Festuca occidentalis* – Western Fescue

Seeds were sown at the beginning of June, 2011. Figure 4 illustrates the plot layout, including the different treatments and random placements of each. The layout design was generated using a random number selection. There were 100 seeds of one species distributed within each plot. Germination counts were conducted weekly throughout June, July, and August 2011. Successful germination was identified in the field with flagging tape.

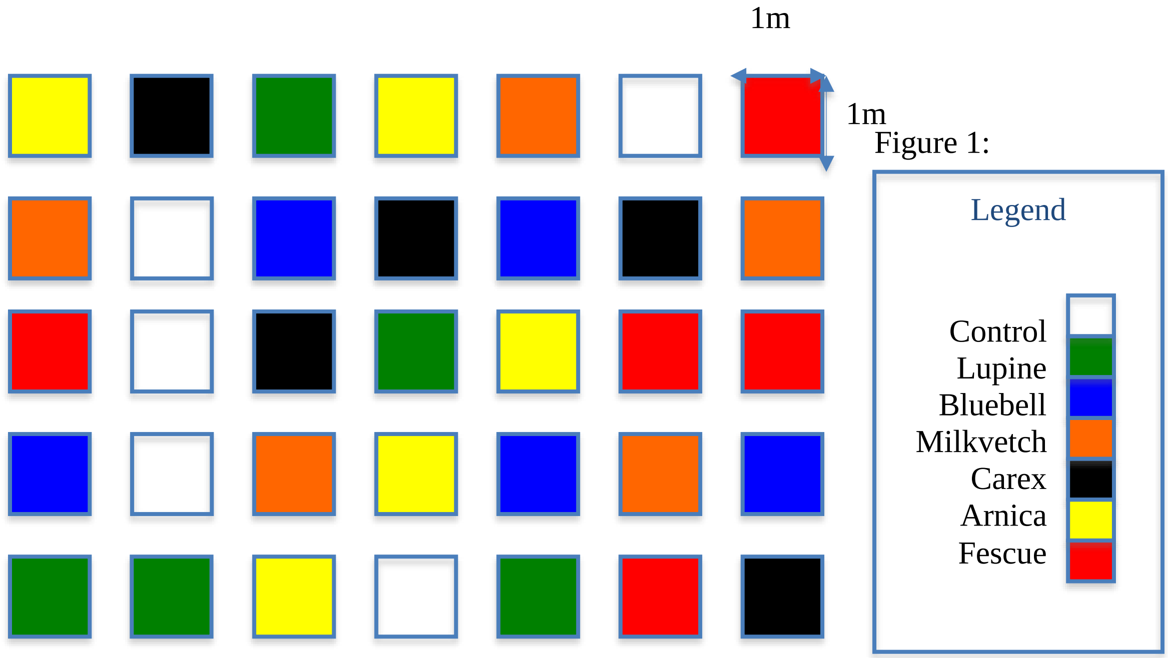

Figure 1: Layout of germination test plots on Kemess Mine's waste rock storage facility in 2011. There were 7 treatments replicated 5 times.

Results

Overall germination rates for each species was less than 10% (Table 1). *Festuca occidentalis* achieved the highest germination rate with 9.4%. *Lupinus arcticus* and *Mertensia paniculata* achieved similar germination rates, as did *Astragalus alpinus* and *Arnica cordifolia*. There were no observations of germination for *Carex macloviana*.

Table 1: Germination results in August 2011, after one growing season.

Treatment	**Germination (%)**
Control – No seeds	0
Lupinus arcticus – Arctic Lupine	5.6
Mertensia paniculata - Tall Bluebell	5.6
Astragalus alpinus - Alpine Milkvetch	1.6
Carex macloviana – Thickhead Sedge	0
Arnica cordifolia – Heart-leaf Arnica	1.2
Festuca occidentalis – Western Fescue	9.4

Discussion

Germination rates of the native seed collected in 2010 and sown in 2011 were low for all species included in the study. The low germination rates observed for all species may be attributed to the lack of pre-sowing treatment conducted for the seeds (i.e. imbibition, mechanical stratification, etc.). The results of this germination study indicate that implementation of direct seeding in future reclamation programs would not be feasible. Germination rates may be positively influenced by supplemental watering, addition of organic matter and mulches. Furthermore, it is unknown whether pre-sowing treatment undertaken for each species would improve germination success rates or be economically feasible on a large scale. Future studies should focus on techniques for improving germination success rates, such as exploring species-specific pre-sowing treatment options and surface preparation techniques that improve habitability of the site.