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Enhancing Natural Succession on Yukon Mine Tailings Sites: a low-input Management Approach

The potential for the native grass Deschampsia caespitosa in northern mine tailings revegetation

By

Alison Clark & Tom Hutchinson

This publication is a modification of Alison Clarks' MSc. thesis

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Submitted to

Mining Environmental Research Group

Alison Clark & Tom Hutchinson

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Non-technical Summary

The revegetation of northern tailings sites presents many challenges. By using plants, which are naturally adapted to both the tailings environment and northern climatic conditions, fewer amendments and intervention will be required. In 2003, vegetation growing on and off the tailings and soil at three Yukon Territory, Canada, mine sites (United Keno Hill, Mount Skukum, and Wellgreen) was assessed and soil samples were collected. Through Canonical Correspondence Analysis (CCA), a statistical program that assesses relationships between plant species and environmental variables, I found that these plant communities are largely governed by a chemical-nutrient gradient (heavy metals and nutrients) and a ground cover gradient (bare and exposed conditions compared with full ground cover). The native grass *Deschampsia caespitosa* L. Beauv. was found colonizing all three tailings sites and its presence was associated with low nutrients, high heavy metal levels, and exposed ground, but it was also a habitat generalist. Five Yukon populations of *D. caespitosa*, originating from mine and uncontaminated sites were tested hydroponically for their tolerance to elevated Ni, Zn, and Cd concentrations. Intrinsic multiple metal tolerance occurred in all populations. In revegetation field trials in the Yukon, I planted seeds and transplants of 7 populations of *D. caespitosa* under different treatments: i) untreated, ii) compost, iii) fertilizer, and iv) combined (compost and fertilizer). At all sites, during the two years of data collection, local and non-local populations, including those from non-contaminated sites were able to establish, grow, and reproduce, even in unamended tailings and despite successive hot and dry summers. *D. caespitosa* also acted as a nurse crop, facilitating invasion of plants from adjacent habitats. The short term results suggest that the inclusion of *Deschampsia caespitosa* as a nurse crop for the revegetation of these northern mine tailings sites will be beneficial.

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Table of Contents

List of Tables

List of Figures

List of Photographic Plates

Mining in the Yukon

Mining is an integral part of the diverse northern culture of the Yukon Territory. It has been the most significant economic sector in the territory during the past 100 years; at times accounting for as much as 36% of the Yukon's Gross Domestic Product (Abbott and Burke 2001). Mining, however, is tightly bound to the ebb and flow of global mineral markets. Periods of low market demand may prompt bankruptcy, mine closures, and mine abandonment.

Few abandoned mine tailings sites in the Yukon were revegetated prior to 1970. In 1972, the *Territorial Lands Act* was ratified to govern natural resources in the Canadian territories. Land use regulations for mineral extraction were established in the Northwest Territories; however, an exemption was made in the Yukon whereby mining was not subject to these regulations. Regulations were anticipated in the following year (Dijkin 2000), but it was not until 1984 that environmental screening for mining activities was legislated.

In 1998, the *Yukon Mining Land Use Regulations* (MLUR) was enacted and is regarded as a positive step forward by many stakeholders. Together with the *Canadian Environmental Assessment Act*, the MLUR mandates that baseline ecological studies are undertaken and provides the minimum environmental standards for exploration, operations, and abandonment, including the re-establishment of a vegetative mat in disturbed areas. Currently, most mines in the territory are inactive and unvegetated, and because their operations ceased prior to 1998, they are grand-fathered under old regulations. However, mineral markets are improving and, in response, exploration and drilling has begun at a few sites (Department of Energy, Mines and Resources 2004). If operations proceed, tailings revegetation programmes will inevitably ensue once mining disturbances have abated.

Northern Mine Tailings Revegetation

Mine tailings are typically a difficult medium for plant establishment and growth. Tailings often contain elevated levels of heavy metals, are low in nutrients and organic matter, and are subject to wind and water erosion. While some plant species and/or adapted populations succeed in colonizing and reproducing in these adverse environments, conditions are often so inhospitable that only scattered patches of vegetation establish (Bradshaw 1984). Thus the process of colonization often proceeds too slowly for many post-mining land-use agendas (Bradshaw and Chadwick 1980). . In the Yukon, for instance, some exploration trenches and overburden piles remain unvegetated decades after activities have ceased (Government of Yukon 1999). Consequently, human intervention to hasten the revegetation process is frequently required.

Northern mine revegetation endeavours often encounter obstacles not typically experienced by their southern counterparts. Northern plants show great tolerance to very low temperatures (Chapin 1987). However, the very low temperatures and short growing seasons decreases the rate of organic decomposition and nutrient cycling, and impedes seed production (Billings 1987; Chapin 1987; White *et al* 2004). The arid conditions of the north also create impediments for plant establishment. Precipitation is low. Low moisture reduces the availability of nutrients, contributes to the salinization of surface soils by the process of calcification (Jorgenson 1988) and inhibits habitat amelioration by microbes, plants, and animals (Iverson and Wali 1992). In contrast, frost heaving on wetter tailings sites is a common phenomenon, making seedling establishment more difficult (Forest Services 1994). It is important, therefore, to use locally adapted species or varieties which are tolerant not only of the harsh chemical and physical conditions of mine tailings, but also to the climatic conditions of the far north. Native Yukon species are clearly climatically adapted to the north, and of these, a smaller sub-set also may show the potential to tolerate the specific chemical-physical challenges of specific tailings sites.

Many recent revegetation projects, nonetheless, have used agronomical cultivars. The agricultural approach has typically been favoured due to the availability of commercial agronomic seed. The use of these agronomic seed mixes, however, has presented some concerns: 1) the introduction of non-native species that have typically been bred for a more southern latitude; 2) the creation of a highly competitive habitat that may obstruct subsequent native plant species colonization; and 3) a short-term solution that requires repeated soil amendments (Mitchell 1979; Jorgenson and Joyce 1994; Piha *et al* 1995; McKendrick 1997; Walker 1999; Marty 2000; Withers 2002). The positive effects of initially seeding short-lived species i.e. many agronomic varieties, on the subsequent long-term recruitment of plants have also recognized (Bradshaw 1997; Gretardottir *et al* 2004). This facilitative use of agronomic species, however, is likely most important on severe sites where initial conditions are very inhospitable; where erosion is an immediate concern; and where large amounts of amendments are undoubtedly required to stabilize surface movement.

At heavy metal contaminated sites, metal tolerant plants play a key role in rehabilitation (Whiting *et al* 2004). Metal tolerant plants can improve aesthetics, reduce blowing dust and sedimentation to water bodies, help build organic content, and improve soil nutrient status more quickly than non-tolerant plants (Tordoff *et al* 1995). Metal tolerant grasses have shown tolerance to additional conditions typical of tailings such as low nutrient status (Jowett 1959), and drought and have been successfully grown in heavy metal laden tailings for several years without signs of regression (Gemmell and Goodman 1978). These tolerant plants modify a site and facilitate colonization by less tolerant species. The physical presence of these plants also serves to reduce fetch and intercept seeds of plants on and off the site which may otherwise be blown across and off the open tailings.

Commonly, restoration includes the extensive application of amendments in order to favour and allow the establishment of highly productive species: the agricultural approach. Despite vigorous and costly efforts, these attempts often beget long-term failure (Marty 2000) and can result in a stagnant plant community (Turner *et al* 1998; Withers 1999). In contrast, the aim of a low input approach is to accelerate the process of natural succession by using ecotypically differentiated populations or adapted species that are tolerant to the site specific conditions. The use of a few species, which have a low nutritional requirement and tolerance to potentially toxic substances at the given site would require fewer 'inputs' or amendments to establish a vegetative cover, and may allow restorationists to plant in unamended tailings (Piha *et al* 1995). In the Yukon, adaptation to the harsh climatic conditions of the far north is necessary. Local and native species fulfill this latter requirement, provided they can also colonize the tailings environment. As well, selecting plant species which are present in the mine vicinity would assist in their colonization and reproduction through genetic exchange and increase the likelihood that the appropriate pollinators and dispersers are present (Marty 2000; SER 2002).

Deschampsia caespitosa, a grass species native to the Yukon Territory, has frequently been documented in and around mine tailings sites in Canada (e.g. Cox and Hutchinson 1979) and Europe (e.g. Von Frenckell and Hutchinson 1993). As such, this species has been the subject of numerous mine tailings revegetation projects. *Deschampsia caespitosa* has demonstrated long-term success (over 15 years) in field plots at Nickel Rim near Sudbury, Ontario and has naturally colonized 1000's of hectares of barren lands around Sudbury following construction of the Super Stack in 1972 (T. Hutchinson 2005; pers comm.).

***Deschampsia caespitosa* L. Beauv. (tufted hairgrass)**

Deschampsia caespitosa has a broad distribution suggesting a high physiological flexibility and the capability to tolerate many environmental conditions (Lawrence 1945; Kawano 1963; Ward 1969). *D. caespitosa* typically inhabits sites with base rich or poor nutrient conditions and impeded drainage (Davy 1980). It occurs in alpine and wet meadows, limestone cliffs, beaches, roadsides (Cody 2000; Kawano 1963), salt marshes (Seliskar 1985), and rich calcareous fens (McClellan *et al* 2003). In the Yukon, *D. caespitosa* is commonly found along lakeshores and riverbanks where it may experience seasonal flooding as well as periods of drought. It also occurs in open sites of the boreal forest, and is a colonizer of cut lines for oil and gas exploration and for hydro. *D. caespitosa* has demonstrated competitive ability under many environmental conditions and yet, it is considered only intermediately gregarious (Grime *et al* 1988).

Deschampsia caespitosa has been found naturally colonizing mine tailings sites around Sudbury and Cobalt, Ontario (Cox and Hutchinson 1979), in Germany and Austria (Von Frenckell and Hutchinson 1993) and in the Yukon Territory (Hutchinson and Kuja 1989). In addition, many of these mine populations have demonstrated tolerance to elevated levels of numerous metals (e.g. Cu, Ni, Co, Zn, Fe, Al, Ag, Ac, and As) (e.g. Von Frenckell and Hutchinson 1993). It seems its natural colonizing ability in the north, its presence at several abandoned Yukon mine sites, its wide range of habitats, and its demonstrated metal tolerance make it a prime candidate for northern mine revegetation.

Project Outline & Objectives

The overall objective of this study was to examine successional trajectories on Yukon mine tailings and develop low-input approaches to direct and manage the pathway of succession. Successful ecosystem restoration requires a fundamental understanding of component species, together with knowledge of how they function as a community. Ecological knowledge permits the development of feasible goals that will realize long-term success (Winterhalder *et al* 2004). Goals help establish social expectations, facilitate comprehensive plans, and set required post-restoration monitoring approaches (Cairns 2000; Ehrenfeld 2000). Good ecological restoration, therefore, incorporates site-specific ecological knowledge and the diverse perspectives and social agendas of stakeholders.

The development of a low input approach to tailings revegetation necessitates a logical sequence of analyses and experimentation (see Piha *et al* 1995). The assessment of plant communities, on the tailings and in adjacent habitats, to locate a few candidate species for revegetation trials is a logical first step; concurrent with the physical and chemical analysis of the tailings. Species selected as candidates, should then be screened for tolerance to metals which are found in elevated concentrations or nutrients which are found in potentially deficient amounts at the given site (Step 2). Subsequent to these findings, small scale field trials can test establishment techniques and *in situ* response of selected plants to amendment treatments (Step 3). Finally, large scale field trials to test combinations of plant species and amendments and the eventual, full scale establishment of vegetation.

This study addressed the first three steps of this low input approach, in part by examining the potential role of the native grass, *Deschampsia caespitosa* in enhancing natural succession and revegetating Yukon mine tailings sites. The goal of the first study was to describe the plant communities on and off the tailings at three mine sites in the Yukon and assess the physical and chemical environmental conditions influencing plant species distribution and colonization. The extensive differences in physical and chemical parameters typically seen between tailings and adjacent soils suggest that the plant communities would be disparate. Resource spatial heterogeneity, however, allows the co-existence of different plant species (Tilman 1993). Some of these species in the surrounding habitats may be specialized to microsites, which possess some of the stressful or disturbed attributes of tailings environment (i.e. low nutrients, organic matter, bare soil, exposed conditions). Other species may be habitat generalists and thus, not specialized to a specific environmental criterion. To this end, an overlap in species distribution among tailings and surrounding habitats may occur and of these species, some may be useful for future revegetation work.

Following the chemical analyses of the tailings, the goal of the second study was to test a number of resident Yukon populations of *D. caespitosa*, from contaminated and uncontaminated sites, for tolerance to potentially phytotoxic levels of three heavy metals that were found in elevated concentrations at the study sites, Ni, Zn, and Cd. Intrinsic tolerance (i.e. no difference in metal tolerance among populations) would suggest that the elevated heavy metal levels would not alone impede the establishment of this species *in situ*. This hypothesis of intrinsic metal tolerance was hydroponically tested in a greenhouse environment. The i*n situ* response of a number of local and non-local populations of *D. caespitosa* under different soil amendment treatments was also examined (the third study). The fact that *Deschampsia ceaspitosa* is naturally found on wide ranging habitats (Lawrence 1945; Kawano 1963; Ward 1969) suggests that all populations could be capable of establishing and reproducing on the tailings environment. Furthermore, the natural occurrence of *D. caespitosa* in nutrient poor habitats (Davy 1980) and the nature of low-nutrient requiring plants (see Chapin 1980) implies that these plants could be capable of growing in unamended tailings and that the application of nutrients will not provide a benefit. These hypotheses were tested in small scale field trials in the Yukon. In addition, the ability of *D. caespitosa* to act as a nurse crop and facilitate the colonization of additional plant species (i.e. nucleated succession) compared with chance colonization on bare tailings was also assessed. By using plants which are adapted to both the harsh and potentially toxic tailings conditions and capable of encouraging the invasion of additional plant species from adjacent habitats, the goal is to facilitate the development of a self-sustaining plant community on the tailings and provide a long-term, low input management approach.

Study One - The physical and chemical factors influencing plant species distribution and colonization on mine tailings sites in the Yukon

The objective of this study was to conduct a site assessment of three mine tailings sites in the Yukon using plant community indices and environmental gradient analyses. Describing the plant communities on and off the tailings and determining the physical and chemical environmental variables which influence the distribution of these plant systems, would allow those most influential variables to be ameliorated or enhanced in order to facilitate succession on the tailings. Due to the sharp delineation seen between tailings and adjacent soils, a clear distinction among soil parameters and plant communities was expected. In general, elevated heavy metals and low nutrient and carbon levels would be more closely associated with the tailings plant community compared with surrounding habitats. However, due to the spatial nature of plant communities and the underlying concept that northern plants typically require lower amounts of organic matter and nutrients, it was predicted that some plant species would inhabit microsites that share characteristics similar to those of the tailings (i.e. low nutrients and organic matter). These species, therefore, could have tolerance to the stresses and disturbances typified by the tailings environment. In contrast, species may be habitat generalists, allowing the colonization of a wider range of environmental conditions. Species revealed through this analysis would be useful for future revegetation work in these far northern mine tailings sites.

Methods

Mine Site Descriptions

Three mine tailings sites in the Yukon were selected for field experiments, Mount Skukum, Wellgreen, and United Keno Hill. These sites were chosen from a number of candidate sites based on access, variation in base geology, latitude, and tailings texture. The natural recovery of these tailings sites was evidently impeded as little colonization had occurred since mine closure. Thus, these sites demonstrated a challenge to revegetation and warranted revegetation research.

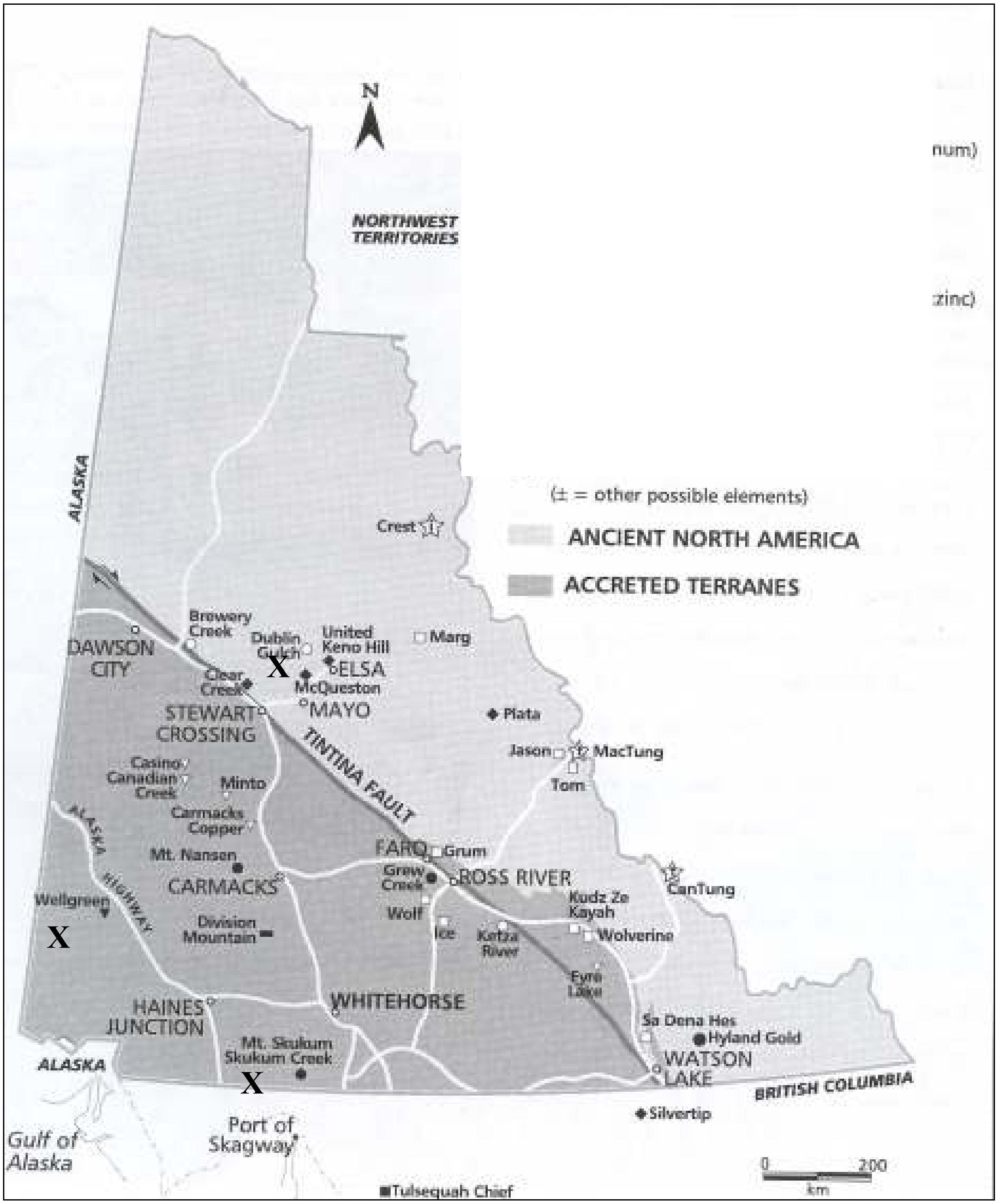

Figure 2.1 Map of the hard rock mining properties in Yukon Territory (Department of Energy, Mines and Resources 2002). My experimental mine sites are demarcated with an X: Mount Skukum United Keno Hill, and Wellgreen.

Mount Skukum

Mount Skukum is located 100 km southwest of Whitehorse in the Wheaton River Valley (60˚14' N and 136˚26' W) (Figure 2.1; Plate 1). Total mean precipitation at the nearest weather station in Whitehorse is 283.3 mm annually. However, Mount Skukum lies within the rainshadow of Montana Mountain and thus, precipitation in this arid region is much lower. Summer temperatures range up to 20˚C and average winter temperatures lie between -10˚ and -20˚C. The surrounding vegetation is typically white spruce and lodgepole pine forest with willow-birch shrub lands.

Mineralization of Mount Skukum is chiefly gold with epithermal quartz-carbonate veins. Mining for gold and silver began in 1984 and was terminated by 1988 when the operating ore deposit was exhausted. A total of 225, 000 tons of ore were removed yielding approximately 80,000 oz of gold through underground mining operations (Jacobson 1990). The resulting tailings pond is approximately 12 ha. To date, Mount Skukum mine is the only Yukon mine that has been acceptably decommissioned (Government of Yukon 1999). It is estimated that 332, 000 oz of gold and 6, 039,000 oz of silver still remain (Department of Energy, Mines and Resources 2002). Tagish Lake Gold Corporation gained ownership in 2000 and resumed exploration in 2003.

Plate 1 Mount Skukum tailings impoundment from tailings dam in June 2003. This area of the tailings, which surrounds the pond, is more densely vegetated compared with most of the tailings impoundment. The experimental plots are not visible, but the general direction is indicated by the arrow (photo by A. Clark 2003).

United Keno Hill Mine

United Keno Hill Mine is located 450 km north of Whitehorse and 300 km east of Dawson (63º 55´N and 135º 25´W) (Figure 2.1; Plate 2). The 15,000 ha mining property lies along the broad McQuesten River valley: characterized by extensive wetlands and lakes in valley bottoms. This region is known for being both the warmest and coldest area of the territory. Summer temperatures often exceed 25˚C and winter temperatures range from -15˚C to -23˚C, with episodes commonly below -50˚C. Precipitation averages 322 mm annually. Permafrost is widespread, but discontinuous.

Underground mining started in 1913 for silver and continued for approximately 70 years, producing silver, zinc and lead. The mineralization consists of discontinuous bands and lenses of silver deposits bottomed out in zinc. The principal ores are pyrites and sulphides. During mining operations approximately 6.5 billion grams of silver were mined. Operations ceased in 1989 and the ensuing tailings impoundment is approximately 47 ha. It is estimated that 415,000 tonnes of mineable ore remains within the property (Department of Energy, Mines, and Resources 2002). Advanced Mineral Technology Ltd. and Nevada Pacific Gold have carried out recent exploration. However, the mine is currently under the care and maintenance of the Yukon Territorial Government and a receivership company.

Plate 2 Primary tailings impoundment of United Keno Hill Mine with the abandoned Hamlet of Elsa in the background. The general location of experimental plots is shown by the arrow (photo by A. Clark 2003).

Wellgreen

The Wellgreen property is located 317 km north-west of Whitehorse in the Kluane ultramafic belt (61°28' N and 139°32' W) (Figure 2.1; Plate 3). Summer temperatures regularly reach 20˚C and winter temperatures rarely remain below -20˚C. Wellgreen lies within the rainshadow of the St. Elias Mountains. Precipitation is therefore low, with periodic heavy events. The Wellgreen tailings are occasionally flooded (e.g. in 2003) and there is a predominant underlying iron hard pan on the tailings. The vegetation surrounding the 7 ha impoundment is primarily a dense white spruce lowland forest.

The Wellgreen region hosts numerous nickel-copper-platinum group elements (PGE) with massive sulphide mineralization. Underground mining occurred intermittingly from 1953-1956 and from 1969-1973. Production in the former period was shortened due to weak metal prices and unexpected erratic distribution of the massive sulphide lenses (Watts, Griffis and McOuat 1989). 171,652 tonnes of ore were mined in this first period. Production in the latter period amounted to 189,211 tonnes of ore (Department of Energy, Mines, Resources 2002), but the mine was closed due to lack of continuity of ore and poor ground conditions. Current reserves are estimated at 50 million tonnes grading 0.36% Ni, 0.35% Cu, and 0.62 g/t Pt (Watts, Griffis and McOuat 1989). Minor trenching and drilling programs in 2000, 2001 and again in 2004 were carried out by the current owner, Northern Platinum Ltd.

Plate 3 Aerial view of the Wellgreen tailings excluding the north end tailings pond. The general location of experimental plots is shown by the arrow. Note the flooded area at the upper end of this site during mid-July; it was more flooded by the end of July (photo by A. Clark 2003).

Sampling Design

Local plant communities in different seral stages were used to assess vegetation and environmental variables and to describe a primary to secondary successional pathway at Mount Skukum, United Keno Hill, and Wellgreen mine sites in the Yukon. Accordingly, each site was divided into four habitat types: tailings, adjacent shrubland surrounding the tailings, and upwind and downwind forest. In each habitat type, transects (beginning a minimum of 10 m from the edge) were set up and 1 m^2 quadrats were placed at 5 m intervals.

Soil Sampling and Analysis

At every 5 m interval two soil samples were taken. The surface vegetation was removed and the top 15 cm beneath it was sampled. The upwind forest samples were considered a background control, since samples were taken in relatively undisturbed areas. The first set of soil samples was air dried and brought back to Trent University, Peterborough, Ontario for analysis. A sub-set was analyzed by ICP-OES for elemental concentrations, including metals and total phosphorus, (strong acid digest: hydrochloric, nitric, perchlorate, hydrofluoric, SGS Lakefield Laboratories, Lakefield, Ontario). As well, Lakefield Research measured 3 sub-samples of tailings from each mine site for Total Sulphur (TS) and Acid Generating Potential (AGP). Percent nitrogen and carbon was analysed by nitrogen-carbon isotope combustion at the Botany Department, University of Toronto, Toronto, Ontario. Further sub-samples were used to measure pH (a 1:10, water slurry shaken for 1 hr and settled for 30 min). The second series of soil samples were air dried for one week and used to assess its water holding capacity using standard non-pressurized methods (Naeth *et al* 1991). Bulk density was also calculated on separate dried samples as weight by volume.

Plant Community Description

The vegetative communities of all three sites were determined. Nomenclature of higher plants followed Cody (2000). In each 1 m^2 quadrat several vegetative parameters were recorded: the plant species present, their abundance and relative cover; the relative cover of litter (plant parts including small woody material with a diameter <2 cm), the amount of woody debris (>2 cm diameter), % cover of moss, lichen, bare soil/tailings, and coarse rock. Relative cover was visually estimated. Tree species above 1 m in height were not included due to the difficulty in assessing relative cover. As well, the depth of tailings (up to 40 cm) and litter were measured. Simpson's Index of Diversity and Shannon-Wiener's Index of Heterogeneity (Odum 1971) were calculated for all sites as well as species richness (the number of species) and frequency.

Results

Physical and Chemical Soil/Tailings Analysis

Table 2.1 The mean metal content of soil and tailings samples from associated habitat types for each mine site, Mount Skukum (MTSK), United Keno Hill (UKHM) and Wellgreen (WG). Values indicated are the means of all samples analyzed and represent total concentrations. Acid Generating Potential (AGP) and Total Sulphur (TS) are the means of three tailings samples only. Standard error is shown in brackets.

Site	Habitat Type	Ag mg/kg	Al mg/kg	As mg/kg	Cd Mg/kg	Cu mg/kg	Fe mg/kg	Ni Mg/kg	Pb mg/kg	Zn mg/kg	AGP	TS
MTSK	Tailings	<2	76500 (±2828.7)	<50	<2	205 (±24.7)	38500 (±353.6)	<20	<50	150 (±21.2)	2.40	0.04%
	Shrubland	<2	52000 (±4596.3)	<50	<2	81 (±48.8)	21000 (±2474.9)	<20	<50	119 (±28.9)		
	upwind forest	<2.	79667 (±3535.5)	<50	<2	10 (±1.37)	26000 (±1018.4)	<20	<50	69 (±9.2)		
	downwind forest	<2	73000 (±1018.4)	<50	<2	12 (±1.17)	30667 (±2112.4)	<20	<50	86 (±4.2)		
UKHM	Tailings	113 (±3.53)	12325 (±556.8)	573 (±54.3)	77 (±9.65)	255 (±14.7)	70000 (±5541.5)	<20	7850 (±724.2)	3500 (±391.1)	0.92	0.56%
	Shrubland	105 (±11.25)	40500 (±12090.2)	720 (±127.3)	134 (±7.07)	150 9 (±7.07)	85000 (±1414.2)	21 (±3.27)	8200 (±282.8)	5550 (±1202.3)		
	upwind forest	<2	18000 (±4949.8)	<50	<2	38 (±47.5)	14000 (±4242.6)	<20	51 (±1.21)	64 (±11.31)		
	downwind forest	2	37000 (±1414.2)	<50	<2	48 (±2.12)	30500 (±1767.8)	24 (±1.41)	120 (±7.07)	120		
WG	Tailings	<2	50333 (±3976.3)	150 (±35.6)	<2	564 (±141.8)	102333 (±20133.4)	610 (±90.4)	58 (±3.67)	64 (±11.31)	97.70	5.16%
	Shrubland	<2	23000 (±2456.5)	<50	<2	28 (±12.8)	17000 (±3568.3)	49 (±3.67)	<50	62 (±3.45)		
	upwind forest	<2	22000 (±1234.2)	<50	<2	29 (±17.4)	15000 (±1598.2)	22 (±5.72)	<50	67 (±9.32)		
	downwind forest	<2	36000 (±3247.6)	120 (±67.8)	<2	3100 (±348.4)	220000 (±12400.4)	760 (±125.6)	68 (±7.89)	80 (±12.3)		

NOTE: MTSK: Mount Skukum Mine; UKHM: United Keno Hill Mine; WG: Wellgreen; AGP: Acid generating potential; TS: Total sulphur

Table 2.2 Mean total macronutrient concentrations, pH and organic content of soil and tailings samples from associated habitat types at each mine site, Mount Skukum (MTSK), United Keno Hill (UKHM) and Wellgreen (WG).. Values indicated are the means of all samples analyzed and represent total concentrations. Standard error is shown in brackets.

Site	Habitat Type	Ca mg/kg	K Mg/kg	Mg mg/kg	Na Mg/kg	% N	P mg/kg	% C	C:N	pH	H_2O g /100g	B_d mg/ cm^3
MTSK	Tailings	33500 (±9545.2)	25500 (±1060.4)	11500 (±353.5)	15000 (±2121.3)	0.09	685 (±38.9)	1.64 (±0.04)	18.2	7.1 (±0.01)	35.31 (±0.52)	1.38 (±0.01)
	Shrubland	28500 (±4596.2)	19500 (±2474.9)	5800 (±1414.2)	12500 (±1060.7)	0.41	795 (±53.03)	6.22 (±0.08)	15.2	6.5 (±0.02)	28.04 (±0.76)	0.69 (±0.01)
	Upwind forest	15500 (±3181.9)	18500 (±353.6)	6050 (±671.8)	19000 (±707.3)	0.09	205 (±38.9)	3.44 (±0.7)	38.2	6.7 (±0.03)	30.97 (±0.81)	0.56 (±0.01)
	Downwind forest	19667 (±192.5)	22667 (±509.2)	9900 (±606.4)	21000 (±333.3)	0.12	547 (±8.39)	2.56 (±0.05)	21.3	6.4 (±0.01)	20.51 (±0.76)	0.39 (±0.01)
UKHM	Tailings	1975 (±54.3)	3775 (±174.8)	1600 (±136.9)	408 (±22.11)	0.02	185 (±4.78)	0.83 (±0.01)	41.5	6.2 (±0.01)	29.06 (±0.24)	1.11 (±0.01)
	Shrubland	2950 (±530.3)	13300 (±6958.9)	3350 (±459.6)	945 (±463.2)	0.08	465 (±208.1)	1.17 (±0.3)	14.6	7.0 (±0.03)	26.38 (±0.25)	1.05 (±0.003)
	Upwind forest	24500 (±6010.4)	4400 (±1202.1)	4550 (±388.9)	2950 (±601.1)	0.9	745 (±81.3)	24.8 (±0.4)	27.6	6.0 (±0.07)	31.43 (±0.31)	0.39 (±0.02)
	Downwind forest	12250 (±3358.7)	7650 (±247.5)	6100 (±282.8)	7050 (±35.6)	0.45	645 (±10.6)	20.8 (±0.9)	46.2	4.8 (±0.09)	34.6 (±0.63)	0.28 (±0.01)
WG	Tailings	30000 (±4055.2)	9000 (±881.9)	14667 (±1503.1)	12200 (±1418.9)	0.29	503 (±35.6)	3.24 (±0.1)	11.2	2.7 (±0.06)	37.81 (±4.0)	1.29 (±0.01)
	Shrubland	38000 (±6520.1)	4600 (±756.3)	8100 (±1308.3)	6100 (±874.5)	1.26	620 (±12.8)	25.4 (±1.6)	20.2	6.2 (±0.14)	19.81 (±1.5)	0.73 (±0.07)
	upwind forest	34000 (±4356.8)	4100 (±1145.8)	6100 (±1110.6)	5900 (±85.3)	0.78	760 (±104.7)	17.4 (±1.7)	22.3	5.1 (±0.09)	32.58 (±3.2)	0.43 (±0.01)
	downwind forest	42000 (±10100.3)	8300 (±2134.8)	15000 (±3002.4)	7300 (±2035.5)	0.57	220 (±57.9)	10.1 (±2.2)	17.7	3.2 (±0.09)	27.59 (±0.4)	0.69 (±0.02)

NOTE: MTSK: Mount Skukum Mine; UKHM: United Keno Hill Mine; WG: Wellgreen; C.N- carbon nitrogen ration; H_2O: water holding capacity; B_d: Bulk density (mg/cm^3).

Plant Communities

Mount Skukum- The mean relative cover, total abundance and frequency of plant species is summarized in Table 2.3. Poaceae was the dominant plant family colonizing the tailings. Vegetation was denser surrounding the tailings pond, consisting primarily of *D. caespitosa* and *Carex aquatilis*. In the sparsely vegetated areas of the tailings, *D. caespitosa* was the dominant plant species, with a mean in sampled quadrats of 10.7%. In the adjacent shrubland, *D. caespitosa* was also the dominant graminoid. Interestingly, out of the 579 individual plants tallied on the MTSK tailings, only 3 individuals were nitrogen fixers: *Oxytropis campestris* (1) and *Shepherdia canadensis* (2).

United Keno Hill- The tailings fell into two moisture regimes: 1) dry and extremely sparsely vegetated; and 2) moist with some densely vegetated areas. Proportionally, Cyperaceae was the dominant family on the tailings, accounting for 88.4% of the plant community. The most common sedge was *Carex aquatilis*, though some patches showed signs of regression. *Equisetum arvense* made up 7.5% of the tailings plant community. Poaceae only proportionally accounted for 2.7% of plant species found growing on the tailings, 0.8% was *D. caespitosa*. There were no nitrogen-fixing species found on the tailings, despite *Hedysarum borealis*, *Oxytropis sp*., *Astagulus sp*., and *Shepherdia canadensis* being found in other disturbed areas of the mine property. Six species of *Salix* were found in adjacent shrublands: only two were found colonizing the tailings, i.e. *S. pulchra* and *S. planifolia* (Table 2.4). These two species of willow were also found growing on the MTSK and WG tailings. The upwind and downwind forests were underlain with permafrost.

Wellgreen- 35.8% of the tailings plant community was made up of members of Poaceae (Table 2.5). *Calamagrostis canadensis* (29.1%) made up large swards of vegetation in moist areas along the tailings-shrubland transitional zone. *D. caespitosa* accounted for 6.5% of species and occupied both moist and drier areas. *Equisetum arvense* was also prevalent (43.6% of species). The shrubland and forest plant communities consist of many members of the Ericaceae family, in total representing 44.6% of the shrubland community and 58.5% of the upwind forest plant community. While *D. caespitosa* was not found growing in the upwind forest, it had extensively colonized the disturbed areas of the downwind forest. It is important to note that most of the plants documented on the WG tailings were actually within the shrubland-tailings transitional zone, as the great majority of the WG tailings areas were completely devoid of vegetation.

The diversity indices and species richness listed in Table 2.6 represents the number of plants species which were recorded along transects, and is not a complete list of plant species found in the tailings impoundment. That said, a number of species had colonized at least patches of the tailings at all three tailings sites. Approximately, 24.3%, 20.5%, and 14.4% of all species recorded along transects at MTSK, UKHM, and WG were found growing on the tailings. At MTSK, 4.0% of plant species documented were confined to the tailings. Similarly, 6.7% of the documented species at UKHM were confined to the tailings, while WG had the highest proportion of species found only on the tailings at 8.7%.

The diversity indices were lowest for the tailings communities relative to the other habitat types. The Shannon-Wiener Index was highest in the shrubland community (i.e. greater evenness) at all sites, but the upwind and downwind forest indices revealed site specific patterns. Interestingly, both Simpson’s Index and Shannon-Weiner were relatively high at MTSK. This may indicate that the MTSK plant communities were dominated by only a few species, but these species were somewhat evenly distributed. Species richness was highest in the shrubland community at all three sites and comparable among sites. A greater number of species have invaded the MTSK tailings while WG had the least. Richness of the WG tailings and downwind forest were similar.

Table 2.3 Summary of mean relative cover (% cover), total abundance (#) and relative frequency (Freq) of all vascular plant species documented along the transects in each habitat type at Mount Skukum (MTSK).

	Tailings			Shrubland			Upwind Forest			Downwind Forest		
	% Cover	#	Freq	% Cover	#	Freq	% Cover	#	Freq	% Cover	#	Documented along the transects
Achillea millefolium	2.3%	6	1.0%	2.2%	17	3.7%	0.0%	0	0	1.3%	3	2.2%
Anemone multifida	0.0%	0	0.0%	2.2%	5	1.1%	0.0%	0	0	2.7%	4	2.9%
Antenarria rosea	0.0%	0	0.0%	7.0%	6	1.3%	0.0%	0	0	0.0%	0	0
Arctostaphylos uva-ursi	0.0%	0	0.0%	20.3%	56	12.3%	6.3%	5	12.8%	24.5%	38	27.7%
Aster sp.	1.0%	1	0.0%	0.0%	2	0.4%	0.0%	0	0	0.0%	0	0
Astragalus alpinus	0.0%	0	0.0%	0.0%	0	0	0.0%	0	0	1.0%	1	0.7%
Betula glandulosa	0.0%	0	0.0%	29.0%	22	4.8%	0.0%	0	0	11.0%	2	1.5%
Calamagrostis purpurescens	10.0%	2	0.3%	5.3%	22	4.8%	0.0%	0	0	0.0%	0	0
Carex aquatilis	12.3%	216	2.8%	0.0%	0	0	0.0%	0	0	0.0%	0	0
Cerastium fontanum ssp. Trivale	4.5%	4	0.7%	3.0%	1	0.2%	0.0%	0	0	0.0%	0	0
Chenopodium rubrum	1.0%	1	0.0%	0.0%	0	0	0.0%	0	0	0.0%	0	0
Deschampsia caespitosa	10.7%	406	70.1%	9.9%	67	14.8%	0.0%	0	0	3.0%	1	0.7%
Eleocharis palustris	3.9%	74	12.8%	0.0%	0	0	0.0%	0	0	0.0%	0	0
Elymus trachycaulus	0.0%	8	1.4%	0.0%	0	0	0.0%	0	0	0.0%	0	0
Empetrum nigrum	0.0%	0	0.0%	0.0%	0	0	9.0%	2	5.1%	0.0%	0	0
Epilobium angustifolium	3.0%	7	1.2%	7.4%	50	11.0%	2.9%	8	20.5%	3.6%	15	10.9%
Epilobium latifolia	4.3%	1	0.2%	0.0%	0	0	0.0%	0	0	0.0%	0	0
Equisetum arvense	6.5%	17	2.9%	0.0%	0	0	0.0%	0	0	0.0%	0	0
Festuca altaica	0.0%	0	0.0%	1.0%	3	0.7%	1.7%	12	30.8%	0.0%	13	9.5%
unknown grass	4.6%	2	0.3%	5.0%	3.0	0	0.0%	0	0	0.0%	0	0
Hordeum jubatum	10.5%	3.75	0.0%	18.0%	35	7.7%	0.0%	0	0	1.0%	1	0.7%

Juniperus horozontalis	0.0%	0	0.0%	0.0%	0	0	0.0%	0	0	6.0%	2	1.5%
Linnaea borealis	0.0%	0	0.0%	0.0%	0	0	5.0%	2	5.1%	6.1%	14	10.2%
Mertensia paniculata	0.0%	0	0.0%	0.0%	0	0	3.0%	1	2.6%	3.3%	4	2.9%
Oxytropis campestris	2.0%	1	0.2%	0.0%	0	0	0.0%	0	0	4.0%	2	1.5%
Penstemon procerus	0.0%	0	0.0%	3.2%	32	7.0%	0.0%	0	0	0.0%	0	0
Picea glauca	2.0%	1	0.2%	6.1%	10	2.2%	0.0%	0	0	1.0%	1	0.7%
Pinus contorta	0.0%	0	0.0%	4.9%	9	2.0%	48.0%	2	5.1%	26.0%	2	1.5%
Polemonium pulcherrimum	0.0%	0	0.0%	3.0%	1	0.2%	0.0%	0	0	0.0%	0	0
Potentilla diversiflora	0.0%	0	0.0%	3.6%	13	2.9%	0.0%	0	0	0.0%	0	0
Potentilla fructicosa	0.0%	0	0.0%	3.0%	7	1.5%	0.0%	0	0	0.0%	0	0
Potentilla uniflora	12.0%	4	0.7%	1.0%	1	0.2%	0.0%	0	0	0.0%	0	0
Rorripa palustris	1.0%	2	0.3%	0.0%	0	0	0.0%	0	0	0.0%	0	0
Rumex sp.	4.3%	4	0.7%	0.0%	0	0	0.0%	0	0	0.0%	0	0
Salix glauca	0.0%	0	0.0%	36.5%	2	0.4%	0.0%	0	0	0.0%	0	0
Salix planifolia ssp. planifolia	9.3%	2	0.3%	28.8%	6	1.3%	4.0%	1	2.6%	0.0%	0	0
Salix pulchra	11.6%	15	2.6%	7.3%	11	2.4%	0.0%	0	0	3.0%	3	2.2%
Senecio lugens	4.0%	3	0.5%	16.0%	7.0	0	0.0%	0	0	0.0%	0	0
Shepherdia canadensis	30.0%	2	0.3%	17.0%	8	0.7%	8.8%	6	15.4%	18.8%	21	15.3%
Solidago multiradiata	0.0%	0	0.0%	3.2%	19	4.2%	0.0%	0	0	0.0%	4	2.9%
Solidago simplex	1.0%	2	0.3%	3.4%	8	1.8%	0.0%	0	0	1.8%	1	0.7%
Trisetum spicatum	3.0%	1	0.0%	3.9%	31	6.8%	0.0%	0	0	0.0%	0	0
unknown herb	0.0%	0	0.0%	5.0%	2.0	0	0.0%	0	0	0.0%	0	0
Vaccinium vitis-idaea	0.0%	0	0.0%	0.0%	0	0	0.0%	0	0	3.0%	5	3.6%
Valeriana dioica	0.0%	0	0.0%	5.0%	7	1.5%	0.0%	0	0	0.0%	0	0

Table 2.4 Summary of mean relative cover (% cover), total abundance (#) and relative frequency (Freq) of all vascular plant species documented along the transects in each habitat type at United Keno Hill (UKHM).

	Tailings			Shrubland			Upwind Forest			Downwind Forest		
	% Cover	#	Freq	% Cover	#	Freq	% Cover	#	Freq	% Cover	#	Freq
Achillea millefolium	0.0%	0	0.0%	0.0%	0	0.0%	3.0%	2	0.8%	0.0%	0	0.0%
Agrostis sp.	2.9%	12	0.1%	0.0%	0	0.0%	0.0%	0	0.0%	0.0%	0	0.0%
Arctostaphylus rubra	0.0%	0	0.0%	0.0%	0	0.0%	6.8%	7	2.9%	0.0%	0	0.0%
Arctostaphylus uva-ursi	0.0%	0	0.0%	0.0%	0	0.0%	5.5%	2	0.8%	0.0%	0	0.0%
Betula glandulosa	0.0%	0	0.0%	0.0%	0	0.0%	21.3%	1	0.4%	9.5%	2	1.5%
Calamagrostis canadensis	2.0%	1	78.6%	0.0%	0	0.0%	0.0%	0	0.0%	0.0%	0	0.0%
Carex aquatilis	29.1%	1153	1.8%	9.3%	187	17.9%	0.0%	0	0.0%	0.0%	0	0.0%
Carex saxatilis	9.7%	27	8.1%	0.0%	0	0.0%	0.0%	0	0.0%	0.0%	0	0.0%
Carex sp.	0.0%	0	0.0%	0.0%	0	0.0%	2.8%	6	2.5%	10.4%	37	27.0%
Cerastium fontanum ssp. trivale	0.0%	0	0.0%	37.2%	36	3.4%	0.0%	0	0.0%	0.0%	0	0.0%
Chenopodium rubrum	2.0%	1	7.5%	0.0%	0	0.0%	0.0%	0	0.0%	0.0%	0	0.0%
Deschampsia caespitosa	4.6%	11	0.1%	7.4%	22	2.1%	0.0%	0	0.0%	0.0%	0	0.0%
Dryopteris sp.	0.0%	0	0.0%	0.0%	0	0.0%	1.5%	1	0.4%	0.0%	0	0.0%
Eleocharis uniglimis	9.0%	109	0.3%	0.0%	0	0.0%	0.0%	0	0.0%	0.0%	0	0.0%
Empetrum nigrum	0.0%	0	0.0%	0.0%	0	0.0%	0.0%	0	0.0%	3.0%	1	0.7%
Epilobium angustifolium	7.0%	5	0.6%	8.0%	109	10.4%	0.0%	0	0.0%	0.0%	0	0.0%
Equisetum arvense	13.7%	110	0.1%	32.1%	321	30.7%	0.0%	0	0.0%	0.0%	0	0.0%
Equisetum scirpoides	0.0%	0	0.0%	0.0%	0	0.0%	2.5%	5	2.1%	1.0%	2	1.5%
Erigeron elatus	0.0%	0	0.0%	3.2%	22	2.1%	0.0%	0	0.0%	0.0%	0	0.0%
Festuca altiaca	0.0%	0	0.0%	0.0%	0	0.0%	4.8%	12	5.0%	0.0%	0	0.0%
Geocaulon lividum	0.0%	0	0.0%	0.0%	0	0.0%	7.0%	8	3.3%	0.0%	0	0.0%
Grass (unidentified)	0.0%	0	0.0%	4.0%	1	0.1%	0.0%	0	0.0%	0.0%	0	0.0%

Hippuris vulgaris	1.0%	1	0.8%	0.0%	0	0.0%	0.0%	0	0.0%	0.0%	0	0.0%
Hordeum jubatum	39.0%	19	1.3%	6.8%	26	2.5%	0.0%	0	0.0%	2.0%	1	0.7%
Ledum groenlandicum	0.0%	0	0.0%	0.0%	0	0.0%	21.2%	83	34.3%	16.9%	42	30.7%
Lupinus arcticus	0.0%	0	0.0%	0.0%	0	0.0%	3.4%	6	2.5%	0.0%	0	0.0%
Parnassia palustris	0.0%	0	0.0%	10.7%	19	1.8%	0.0%	0	0.0%	0.0%	0	0.0%
Picea mariana	0.0%	0	0.0%	0.0%	0	0.0%	35.0%	41	16.9%	39.3%	10	7.3%
Plantanthera hyperborea	0.0%	0	0.0%	4.7%	61	5.8%	0.0%	0	0.0%	0.0%	0	0.0%
Polygonum sp.	2.0%	3	0.2%	0.0%	0	0.0%	0.0%	0	0.0%	0.0%	0	0.0%
Populus balsamifera	0.0%	0	0.0%	5.9%	40	3.8%	0.0%	0	0.0%	0.0%	0	0.0%
Populus tremuloides	0.0%	0	0.0%	6.5%	32	3.1%	0.0%	0	0.0%	0.0%	0	0.0%
Rosa acicularis	0.0%	0	0.0%	0.0%	0	0.0%	12.0%	2	0.8%	0.0%	0	0.0%
Salix alaxensis	0.0%	0	0.0%	4.7%	5	0.5%	0.0%	0	0.0%	0.0%	0	0.0%
Salix arbusculoides	0.0%	0	0.0%	2.5%	2	0.2%	0.0%	0	0.0%	0.0%	0	0.0%
Salix bebbiana	0.0%	0	0.0%	28.3%	18	1.7%	0.0%	0	0.0%	0.0%	0	0.0%
Salix glauca	11.7%	6	0.4%	9.2%	41	3.9%	20.3%	3	1.2%	10.0%	1	0.7%
Salix pulchra	1.0%	1	0.1%	5.0%	59	5.7%	0.0%	0	0.0%	0.0%	0	0.0%
Salix reticulate	0.0%	0	0.0%	2.0%	4	0.4%	0.0%	0	0.0%	0.0%	0	0.0%
Salix sp. (prostrate)	0.0%	0	0.0%	0.0%	0	0.0%	5.0%	1	0.4%	0.0%	0	0.0%
Taraxacum officinale	0.0%	0	0.0%	4.0%	39	3.7%	0.0%	0	0.0%	0.0%	0	0.0%
Vaccinium uliginosum	0.0%	0	0.0%	0.0%	0	0.0%	12.6%	47	19.4%	8.1%	34	24.8%
Vaccinium vitis-idaea	0.0%	0	0.0%	0.0%	0	0.0%	7.2%	15	6.2%	5.1%	7	5.1%

Table 2.5 Summary of mean relative cover (% cover), total abundance (#) and relative frequency (Freq) of all vascular plant species documented along the transects in each habitat type at Wellgreen (WG).

	Tailings			Shrubland			Upwind Forest			Downwind Forest		
	% Cover	#	Freq	% Cover	#	Freq	% Cover	#	Freq	% Cover	#	Freq
Arctostaphylos rubra	0.0%	0	0.0%	8.2%	111	37.2%	4.7%	75	51.0%	5.0%	26	16.7%
Arctostaphylos uva-ursi	0.0%	0	0.0%	7.6%	10	3.4%	16.0%	2	1.4%	0.0%	0	0.0%
Betula glandulosa	0.0%	0	0.0%	23.3%	7	2.3%	0.0%	0	0.0%	0.0%	0	0.0%
Calamagrostis canadensis	9.1%	281	29.1%	2.7%	4	1.3%	0.0%	0	0.0%	0.0%	0	0.0%
Calamagrostis purpurescens	0.0%	0	0.0%	0.0%	0	0.0%	1.0%	1	0.7%	0.0%	0	0.0%
Carex aquatilis	27.8%	29	3.0%	0.0%	0	0.0%	0.0%	0	0.0%	10.0%	20	12.8%
Carex diandra	4.0%	6	0.6%	0.0%	0	0.0%	0.0%	0	0.0%	0.0%	0	0.0%
Carex saxatilis	7.0%	117	12.1%	0.0%	0	0.0%	0.0%	0	0.0%	0.0%	0	0.0%
Deschampsia caespitosa	27.3%	63	6.5%	0.0%	0	0.0%	1.0%	4	2.7%	15.0%	8	5.1%
Empetrum nigrum	0.0%	0	0.0%	0.0%	0	0.0%	9.2%	5	3.4%	0.0%	0	0.0%
Epilobium angustifolium	0.0%	0	0.0%	0.0%	0	0.0%	3.0%	1	0.7%	0.0%	0	0.0%
Equisetum arvense	16.8%	421	43.6%	0.0%	0	0.0%	0.0%	0	0.0%	2.5%	6	3.8%
Equisetum scirpoides	0.0%	0	0.0%	3.5%	23	7.7%	0.0%	0	0.0%	1.0%	1	0.7%
Festuca altaica	0.0%	0	0.0%	7.3%	21	7.0%	7.0%	10	6.8%	4.5%	4	2.6%
Gentiana propinqua	0.0%	0	0.0%	5.0%	3	1.0%	0.0%	0	0.0%	0.0%	0	0.0%
Geocaulon lividum	0.0%	0	0.0%	0.0%	0	0.0%	3.3%	12	8.2%	0.0%	0	0.0%
Hedysarum borealis	0.0%	0	0.0%	4.3%	5	1.7%	0.0%	0	0.0%	0.0%	0	0.0%
Hordeum jubatum	0.0%	0	0.0%	2.0%	1	0.3%	0.0%	0	0.0%	0.0%	0	0.0%
Ledum groenlandicum	0.0%	0	0.0%	1.0%	1	0.3%	3.0%	1	0.7%	16.2%	22	14.1%
Lupinus arcticus	0.0%	0	0.0%	0.0%	0	0.0%	10.0%	11	7.5%	0.0%	0	0.0%
Mertensia paniculata	0.0%	0	0.0%	0.0%	0	0.0%	2.0%	1	0.7%	0.0%	0	0.0%
Parnassia palustris	0.0%	0	0.0%	2.0%	2	0.7%	0.0%	0	0.0%	0.0%	0	0.0%
Pedicularis orderi	0.0%	0	0.0%	4.5%	4	1.3%	0.0%	0	0.0%	0.0%	0	0.0%

Petasites frigidus	0.0%	0	0.0%	2.0%	3	1.0%	0.0%	0	0.0%	0.0%	0	0.0%
Phleum pratense	2.0%	1	0.1%	0.0%	0	0.0%	0.0%	0	0.0%	0.0%	0	0.0%
Picea glauca	0.0%	0	0.0%	25.0%	13	4.4%	30.3%	4	2.7%	31.7%	10	6.4%
Polygonon amphibium ssp. Laevimarginatum	9.4%	44	4.6%	0.0%	0	0.0%	0.0%	0	0.0%	0.0%	0	0.0%
Potentilla fructicosa	0.0%	0	0.0%	8.6%	15	5.0%	0.0%	0	0.0%	4.0%	2	1.3%
Rorripa palustris	3.0%	1	0.1%	0.0%	0	0.0%	0.0%	0	0.0%	0.0%	0	0.0%
Rosa acicularis	0.0%	0	0.0%	0.0%	0	0.0%	3.0%	1	0.7%	11.0%	6	3.8%
Salix alaxensis	0.0%	0	0.0%	4.0%	1	0.3%	0.0%	0	0.0%	0.0%	0	0.0%
Salix arbusculoides	0.0%	0	0.0%	10.0%	4	1.3%	0.0%	0	0.0%	0.0%	0	0.0%
Salix bebbiana	0.0%	0	0.0%	8.6%	27	9.1%	11.0%	1	0.7%	9.7%	40	25.6%
Salix glauca	0.0%	0	0.0%	15.0%	6	2.0%	13.0%	2	1.4%	19.2%	12	7.7%
Salix planifolia ssp. Planifolia	0.0%	0	0.0%	0.0%	0	0.0%	18.0%	2	1.4%	0.0%	0	0.0%
Salix pulchra	5.5%	2	0.2%	14.0%	2	0.7%	0.0%	0	0.0%	0.0%	0	0.0%
Senecio leguns	0.0%	0	0.0%	3.0%	4	1.3%	1.0%	1	0.7%	0.0%	0	0.0%
Shepherdia canadensis	0.0%	0	0.0%	0.0%	0	0.0%	21.0%	3	2.0%	0.0%	0	0.0%
Solidago simplex	0.0%	0	0.0%	3.0%	6	2.0%	0.0%	0	0.0%	0.0%	0	0.0%
Taraxacum officinale	0.0%	0	0.0%	3.5%	3	1.0%	3.0%	1	0.7%	0.0%	0	0.0%
Vaccinium ulinginosum	0.0%	0	0.0%	3.3%	5	1.7%	5.7%	4	2.7%	0.0%	0	0.0%
Vaccinium vitis-idaea	0.0%	0	0.0%	7.0%	6	2.0%	10.5%	4	2.7%	0.0%	0	0.0%

Table 2.6 Mean Index values and Species Richness of the four habitat types at each test mine site, Mount Skukum (MTSK), United Keno Hill (UKHM), and Wellgreen (WG).

	Simpson's Index			Shannon-Weaver			Species Richness		
	MTSK	UKHM	WG	MTSK	UKHM	WG	MTSK	UKHM	WG
Tailings	0.46	0.37	0.30	1.25	0.86	1.46	21	14	10
Shrubland	0.92	0.15	0.17	2.73	2.30	2.47	25	25	26
Upwind Forest	0.84	0.20	0.29	1.88	2.03	1.99	11	17	22
Downwind Forest	0.87	0.24	0.15	2.37	1.64	2.11	20	10	11

Note: Mount Skukum -MTSK; United Keno Hill – UKHM; Wellgreen – WG. Also, data refers to vegetated parts of the tailings while large areas of all tailings were unvegetated.

Species-Environment Interactions

At each site, the selected habitat types were grouped based on environmental variables, suggesting minimal overlap in physical and chemical composition among the habitats. At both MTSK and WG, the upwind forest samples were clustered the furthest away from the heavily disturbed tailings samples and generally, had the least overlap in species (Figures 2.2, 2.4).

At MTSK, 24.2% of variance was explained by axis 1. Total Cu concentration explained most of the variation over the study area, but depth of tailings, Zn, bulk density, bare ground, and pH were also highly associated on the positive end (Figure 2.2). These environmental variables typified the MTSK tailings. On the negative end of axis 1, litter and downed woody debris (DWD) were large influences. To this end, the first axis was considered a ground cover gradient as the tailings were extremely exposed compared with the rich moss, lichen, litter cover and woody debris in the forested and shrubland communities. The second axis at MTSK explained a smaller proportion of the plant species distribution (15.1%). It was characterized primarily by total Al, Mg, and K on the one hand, and carbon, nitrogen, and total phosphorus on the other. This gradient was considered a chemical-nutrient gradient.

Species formed clusters around their primary habitat type. However, species such as *D. caespitosa*, *Cerastium fontanum*, *Salix planifolia*, *S. pulchra*, *Aster sp*, and *Senecio leguns*, were located in the centre of the ordination, closer to the shrubland community. In general, these species were intermediate with axis 2, suggesting a less specific nutrient requirement. Species, such as *Antennaria rosea*, *Valeriana dioica,* and *Salix glauca* were strongly associated with the lower nutrient end and where intermediately associated with exposed ground. Species diversity increased with increasing amounts of carbon, nitrogen and phosphorus.

At UKHM, 24.2% of variance explained by axis 1. Heavy metals such as Pb, Fe, Cd, and Zn explained most of the variation on the negative end of the gradient; base cation minerals i.e. Ca, Na, and Mg as well as nutrients such as nitrogen, phosphorus, and carbon, accounted for most of the variation on the positive end (Figure 2.3). The first axis was classified as a chemical-nutrient gradient. This reflected the nutrient poor-heavy metal rich composition of the tailings and shrubland soils, which were themselves overlaying tailings, compared with the more nutrient rich and organic forest soils. The second axis explained a smaller proportion of variance, but was characterized as a ground cover gradient due to the strong influence of ground cover on one end, and lack thereof on the other (Figure 2.3).

Plant species clustered around a given habitat type. Generally, an increase in diversity corresponded to an increase in ground cover, though species richness and heterogeneity were greatest at intermediate levels of carbon and nitrogen according to the model and the diversity indices. Species associated with the shrubland community were affiliated with the lower and intermediate end of the nutrient spectrum. *D. caespitosa* and *H. jubatum*, along with *S. pulchra*, *P. balsamifera*, showed little affiliation with any habitat, i.e. they were habitat generalists. *A. uva-ursi*, and *Lupinus arcticus* were most correlated to nutrient rich environments, though the presence of a legume may well be the reason for higher nitrogen levels.

The WG ordinations indicated that 24.5% of the variance was significantly explained by axis 1. Ni explained the largest portion of CCA axis 1 from the negative side, followed by total Mg, K and Na (Figure 2.4). These variables were were primarily related to the tailings plant community and to a lesser degree, the downwind forest. Carbon, nitrogen, and pH influenced the positive side of the gradient (Table 2.7). These environmental variables were generally higher in the shrubland community. CCA axis 1 was best classified as a chemical-nutrient gradient that shifts from high nutrients and near neutral pH to low nutrients and extremely acidic pH. CCA axis 2 was explained primarily by water holding capacity, bulk density, tailings depth, and bare ground. These variables typified the bare and exposed nature of the tailings. Ground covers i.e. moss, lichen, and downed woody debris also provided some explanation for this axis. Similar to the other sites, axis two was considered a ground cover gradient.

The plants species at WG were more dispersed than at the other two sites and may reflect a more spatially heterogeneous environment. An increase in carbon, nitrogen, and pH, corresponded to an increase in diversity. Similarly, an increase in ground cover corresponded to an increase in diversity. Many of the shrubland species were strongly associated with high nutrients and also very exposed conditions. Again, the presence of a legume may have been one factor in this high nutrient affiliation. Similarly, species documented only in the upwind forest were far removed from the tailings and downwind forest communities. *D. caespitosa* and *C. aquatilis* were clumped within the tailings community, albeit their occurrences were similar, if not greater in the downwind forest. Their species scores indicated that they were both associated with the low nutrient spectrum, but were intermediate in terms of ground cover. *Ledum groenlandicum* appeared in the middle of the ordination and its species scores also indicated that it may be a habitat generalist.

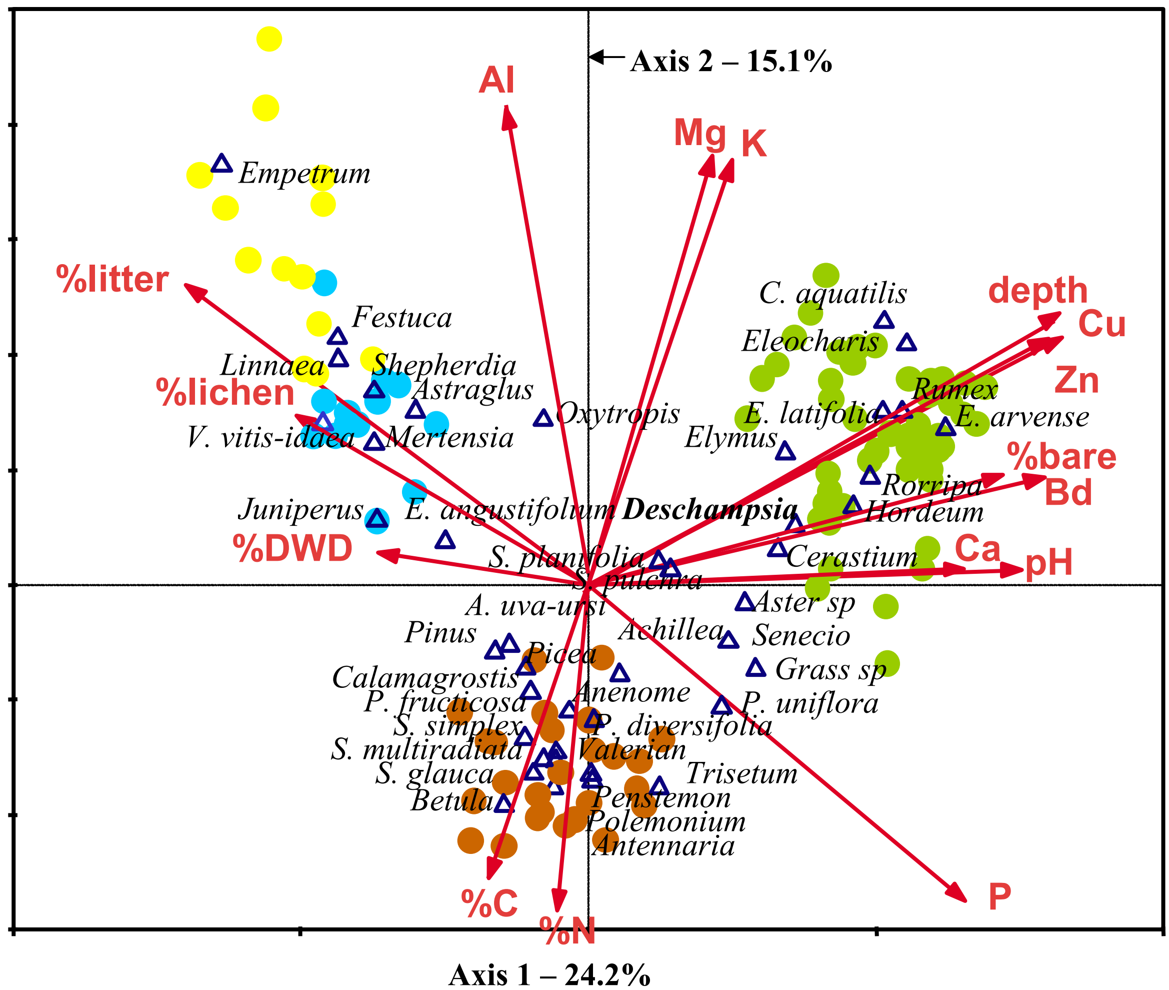

Figure 2.2 Mount Skukum CCA ordination showing the relationships between quadrats (circles), species (triangles) and environmental variables (red arrows). The colour coding of samples is as follows: green –tailings; brown- shrubland; yellow- upwind forest; blue-downwind forest. See Table 2.3 for full species names. Environmental variable abbreviations are as follows: Bd- Bulk density; %bare-percent bare ground; depth-depth of tailings; % N- percent nitrogen; %C- percent carbon; pH- soil pH; %litter – relative cover of ground litter; %lichen- relative cover of lichen; %DWD-relative cover of downed woody debris. All remaining listed elements are measured in total concentration.

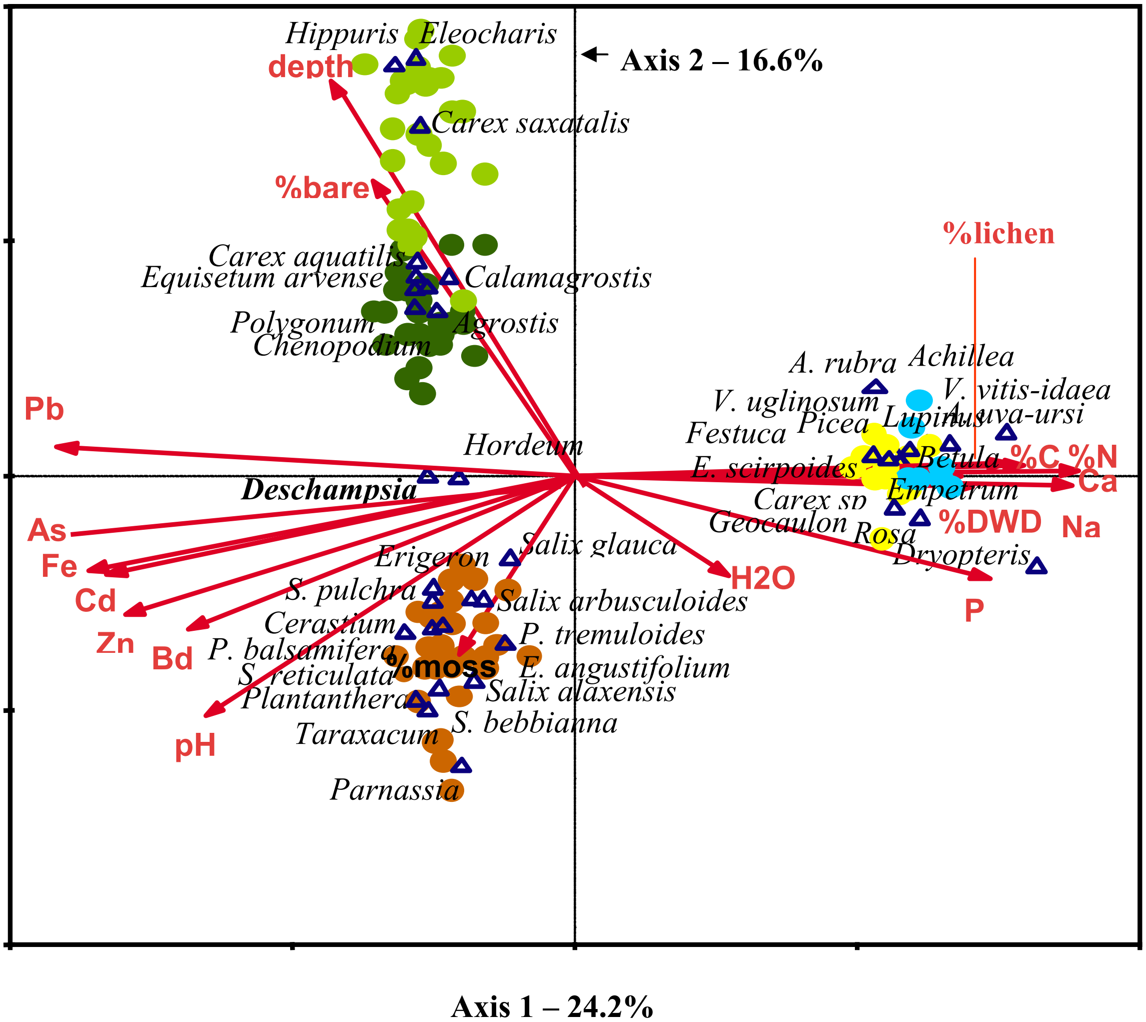

Figure 2.3. United Keno Hill CCA ordination showing the relationship between quadrats (circles), species (triangles), and environmental variables (red arrows). The colour coding of samples is as follows: light green –moist tailings; dark green-dry tailings; brown-shrubland; yellow- upwind forest; blue- downwind forest. See Table 2.4 for full species names. Environmental variable abbreviations are as follows: H2O-water holding capacity; %bare-percent bare ground; %DWD- relative cover of downed woody debris; %lichen-relative cover of lichen; depth-depth of tailings; Bd- Bulk density; % N- percent nitrogen; %C- percent carbon; pH- soil pH. All remaining listed elements are measured in total concentration.

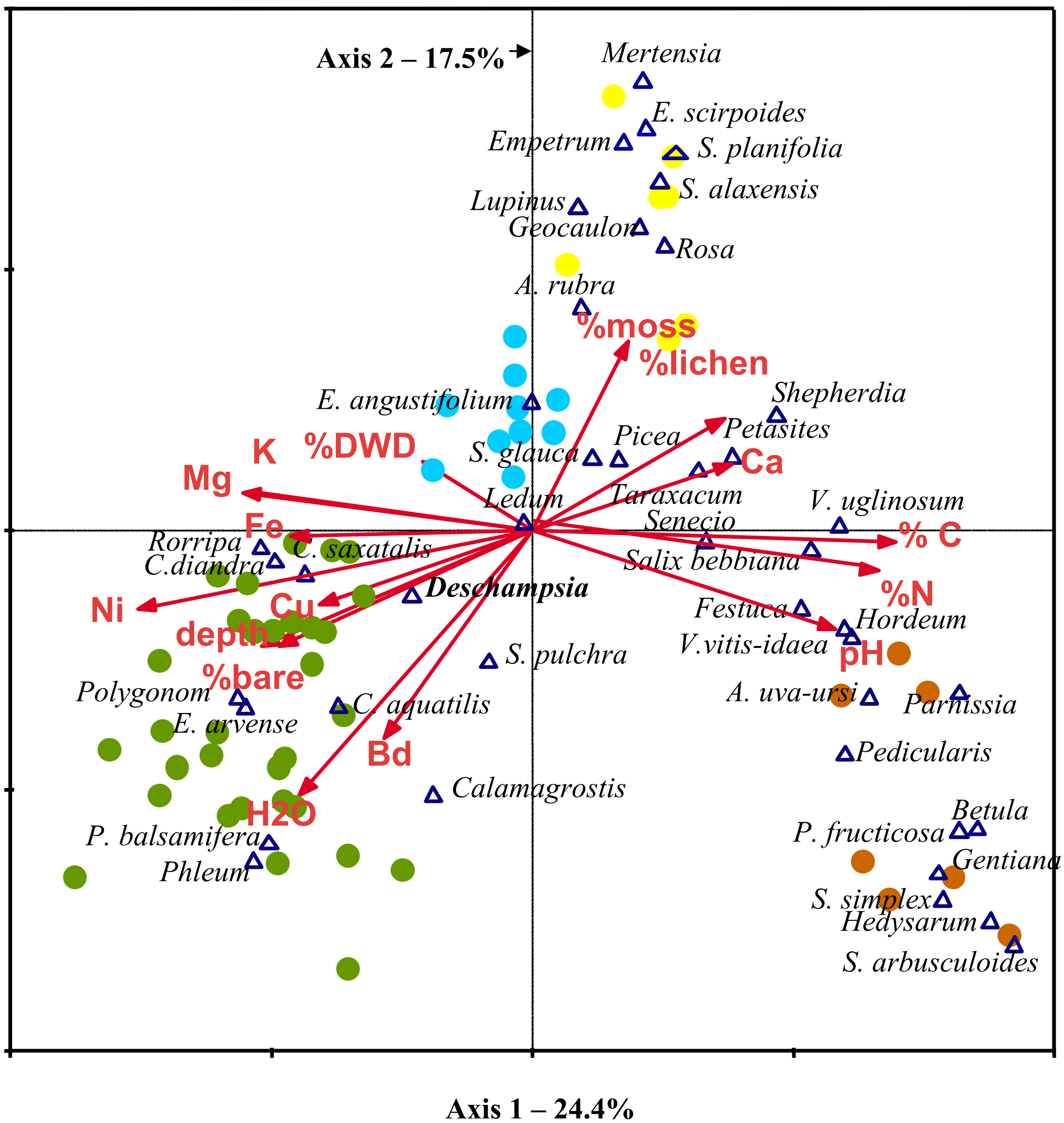

Figure 2.4. Wellgreen CCA ordination showing the relationships between quadrats (circles), species (triangles) and environmental variables (red arrows). The colour coding of samples is as follows: green –tailings; brown- shrubland; yellow- upwind forest; blue- downwind forest. See Table 2.5 for full species names. Environmental variable abbreviations are as follows: H2O-soil water holding capacity; Bd- Bulk density; bare- percent bare ground; depth-depth of tailings; % N- percent nitrogen; %C- percent carbon; pH- soil pH. All remaining listed elements are measured in total concentration.

Discussion

The results of this study have shown that while both the site-specific environmental variables (Tables 2.1, 2.2) and plant communities (Tables 2.3, 2.4, 2.5) clearly differed, there was overlap in those species colonizing the tailings. The pre-selected habitats (i.e. tailings, shrubland, upwind and downwind forest) and their associated species clustered separately in the ordination diagrams. Nevertheless, some species such as *Deschampsia caespitosa* and *Salix sp*. were shown to be primarily habitat generalists as predicted. Additional species also emerged, which while not found on the tailings may well be capable of tolerating the stress and disturbance of the tailings conditions, owing to their strong affiliation with low nutrients and/or exposed conditions, or, in some cases, their correlation to elevated metal concentrations, such as *Erigeron elatus*, *Agrostis sp*., and *Equisetum arvense*. This is probable evidence of microsite variation within the shrubland and forested ecosystems.

Canonical Correspondence Analysis (CCA) constructed an axis, which represents a chemical-nutrient gradient (i.e. C, N, P), as well as a ground cover gradient at each site (Figures 2.2, 2.3, 2.4). The fundamental successional processes at each site are therefore comparable. The delineated axes explained more variation (i.e. 40-42%) in species distribution than some similar studies (e.g. Wiegleb and Felinks 2001; Gretarsdottir *et al* 2004) and many of the environmental variables were highly correlated, suggesting both statistical and ecological significance. Some of these positive correlations were a direct function of the base chemical geology of the tailings (e.g. Ni-Cu, Zn-Cd-Pb), while the tailings were negatively correlated with carbon and nitrogen. In addition, a number of other chemical elements (e.g. Al, Mg, K and Na) correlated, likely as a result of the mineral composition of the tailings and surrounding soils. Unexplained variation at each site (~60%) is likely attributed to chance.

The relative importance of these axes varied among sites. At MTSK, ground cover, or the lack thereof (i.e. exposed conditions), explained most of species distribution. This suggests that the colonization of MTSK tailings, with its lower heavy metal burden, and higher pH, is impeded by water relations and microsite opportunities. The presence of ground cover, such as litter, downed woody debris, lichen, or moss help stabilize surfaces, retain moisture, reduce frost heaving and contribute organic matter (Hodkinson *et al* 2003; Groeneveld and Rochefort 2005). They can also obstruct seeds that would otherwise be blown across and off the open tailings (Li *et al* 2004). Litter and downed woody debris were only sporadically located on the tailings and it is largely in these areas that vegetation has been able to colonize. The non-random occurrence of ground cover, including downed woody debris will, therefore, likely encourage greater colonization and plant species diversity on the tailings.

Plant species distribution at UKHM and WG, on the other hand, was explained more by chemistry: nutrients such as carbon (i.e. nutrients derived from the organic matter), nitrogen, phosphorus, and base cations, as well as heavy metals. Competition for very limited nutrients plays a particularly important role during primary succession and is a dominant factor in plant allocation and regenerative strategies (Grime 1979; Elgersma 1998; Wali 1999; Lichter 2000; Haas and Kuser 2003; Walker 2003; Day *et al* 2003). Plants derive many nutrients from soil organic matter. Organic matter typically: accrues with community development (Elgersma 1998); increases nitrogen levels (Tilman 1988); and enhances water holding capacity (Walker and Powell 2001). To this end, it becomes evident that most nutrients and carbon were associated with the more diverse and later seral shrubland communities at MTSK and WG, and with the forested ecosystems at UKHM. The latter association may be due to the local presence of permafrost, whereby the 'soils' consists primarily of undecomposed plant matter and thus, contain high carbon levels (White *et al* 2004).

C/N ratios in the UKHM tailings and soils as well as in MTSK upwind forest soils were high. It is generally accepted that a C/N ratio at or below the range 20-25 will allow considerable net N mineralization (Harmsen and Kolenbrander 1965; as cited in Wali 1999). Rates higher than this can indicate that mineralized N is being completely used by microorganisms (Weintraub and Schimel 2003) or that *in situ* plants are highly productive, but decomposition rates are retarded (Schafer and Nielson 1979). Northern soils are known to be nitrogen limited. Nitrogen levels in some Alaskan soils range from 0.67% total N in tussock soil to 2.51% total N in nutrient-rich wet meadows (Weintraub and Schimel 2003). Nitrogen levels at WG were comparable with this range (e.g. 1.46% nitrogen in shrubland soils), likely attributed, in part, to the presence of nitrogen-fixing species such as *Shepherdia canadensis* and *Hedysarum borealis*. However, MTSK and UKHM nitrogen levels were much lower. Total phosphorus levels in these Yukon soils and tailings were also rather low, but comparable to other arid and northern regions (see Brady 1990).

On mine tailings sites, annual species often initiate colonization shortly after abandonment and their successive offspring persist for several years due to poor nutrient status and low moisture (Wali 1999). Tilman and Wedin (1991) have found that species requiring less nitrogen often initiate invasion early in succession, while those species needing greater amounts of nitrogen require several years to invade. Early successional and annual species, such as *Achillea millefolium* and *Chenopodium album,* have shown a greater ability to extract soil nitrogen, independent of total soil nitrogen concentrations (Tilman 1986), while tolerance to low nutrients, in particular nitrogen, is frequently exhibited by plants from northern and arid regions (Chapin 1980; Chapin *et al* 1986; references therein; Piha *et al* 1995). Moreover, Bradshaw has repeatedly found that metal tolerant species invading UK mine sites also have a remarkable ability to colonize nutrient deficient sites (in Bradshaw and Chadwick 1980).

The only annuals documented, *Rorripa palustris* at MTSK and WG, *Chenopodium rubrum* at MTSK and UKHM, and *Polygonum sp*. at MTSK, were affiliated with low nutrients (Figures 2.2, 2.3, 2.4), chiefly because these species were only found on the tailings. Annuals are not prevalent in northern ecosystems and usually serve to fill the void following moderate disturbance in these perennial dominated systems (Grime 1979). In the present study, many of the perennial species found in adjacent shrublands and on the tailings were also associated with lower nutrient status or elevated heavy metals as predicted for this study and as suggested by Chapin *et al* (1986), Piha *et al* (1995), and Bradshaw (in Bradshaw and Chadwick 1980) (e.g., *Calamagrostis canadensis*, *Equisetum arvense*, *Carex aquatilis, Achillea millefolium*). Other species, in contrast, were not strongly correlated with either high or low nutrient levels (e.g *D. caespitosa*, *Epilobium angustifolium Cerastium sp*., *Salix sp*., *Populus. sp.* Tables 2.3, 2.4, 2.5; Appendix A). This suggests that some species growing in adjacent habitats or on the tailings may be classified as stress-tolerators (i.e. tolerant of low nutrients or heavy metals), while others are habitat generalists, and thus both may possess a high colonization potential (Pywell 2003).

Elevated heavy metal concentrations can have considerable implications for plant growth and establishment. Metal solubility is governed especially by pH, but also concomitantly by physical factors such as particle size (Ernst 1996; Tordoff *et al* 2000; Seregin and Ivanov 2000; Krazaklewski and Pietrzykowski 2002; Wong 2003) and biological conditions such as organic matter (Bech *et al* 1997; Mulė and Melis 2000; Choi 2000) and microbial decomposition (Balabane *et al* 1999). Fine structure or texture increases the accessibility of metals to plant roots and water (Ernst 1996). High bulk density values suggested a fine tailings composition at all three sites. The extreme compaction at WG, moderate compaction at MTSK, and susceptibility to wind erosion at UKHM confirmed this.

In this study, since only total metal concentrations were measured, biological availability is somewhat speculative. There is a strong probability, nonetheless, that the high acidity of the

WG tailings (pH 2.7) and downwind forest soils (pH 3.2) has increased the solubility of metals in soil solution. The relatively high organic content (3.2%) may offer some ameliorating effects (i.e. metal binding), and indeed, may explain why plants on the tailings have colonized these microsites only. In contrast, the pH of 7.1 at MTSK indicated that many metals such as Zn, Pb, and Cu would be largely unavailable. However, preliminary revegetation trials with agronomic species conducted by Mount Skukum Gold Corp. in 1988 revealed accumulation of Al (1652 mg/kg in grasses) and Cd (4.0 mg/kg in willow) in aerial plant parts at concentrations that could pose a threat to local grazing moose, horses, and sheep (Jacobson 1990). This occurrence verifies that a plant's capacity to accumulate or be influenced by a given metal is not simply a function of its concentration in the soil. A decrease in pH around the rhizosphere would increase the solubility of Zn (150 mg/kg) and Cu (205 mg/kg) in the MTSK tailings, particularly in light of the low organic content (Glinski and Lipiec 1990). In fact, the high correlation of Cu and Zn to axis 1 (Tables 2.7, 2.8) may suggest a greater metal influence than has currently been recognized.

The UKHM shrubland community has succeeded directly over old tailings, and despite having significant soil development, tailings inevitably contribute to the shrubland soil composition. This may explain the unexpected strong association of the heavy metals (Zn, Pb, Cd) to the shrubland community rather than the tailings (Figure 2.3). This unanticipated feature of the shrubland could stem from a change in tailings composition during the over 70 years of mining. The greater extent of organic matter in the shrubland soils relative to tailings may also be responsible as metals bind to organic material. The elevated metal burden was equivocally demonstrated by some shrubland species, such as *Arctostaphylos uva-ursi*, *Carex aquatilis*, and *Equisetum arvense*, which frequently exhibited signs of chlorosis and blackened foliage (A. Clark; personal observation). The pattern of this chlorosis was dissimilar to that of chlorosis from nitrogen deficiency, though this may well be an additional factor. *C. aquatilis* and *E. arvense* were also prevalent on the moist tailings, though the visible signs of stress were much more pronounced in the shrubland. Their presence in both of these habitats, but increased visible stress in the shrubland, may indicate that these species are remnants of early colonists of the shrubland. This stress, therefore, could be a result of either prolonged metal exposure or changes in their local environment caused by the colonization of later successional species.

The plant community assessments indicates that selective pressures were seemingly steepest on the WG tailings: 1) the least percentage of potential plant species (i.e. those found in the surrounding habitats) were found growing on the tailings despite having the largest species pool to draw from (Table 2.6); and 2) the highest percentage of species on the tailings at WG were confined to the tailings, suggesting that the suite of plants which have successfully colonized the WG tailings may possess unique capabilities or have developed a site-specific ecological niche. The extreme nature of the WG tailings i.e. acidic (pH 2.7), prevalent iron hardpan, elevated concentrations of Ni, Cu, Fe, and S, as well as the fact that no plants have surpassed the transitional zone which borders the tailings in over 30 years, supports the notion that selection pressures from these tailings have been severe.

The reverse argument implies that the MTSK tailings have imposed the least amount of selective pressure. Diversity indices and species richness of the tailings community were greater at this site. As well, soils in the region are particularly mineral and the valley as a whole is very arid. The necessary invasive jump to the mineral and drought prone tailings should, therefore, be less abrupt here. However, a large portion of the MTSK tailings remain uncolonized 17 years after mining operations have ceased. The neutral pH, in addition to the physical nature of the tailings has potentially acted as a hindrance to invasion by boreal species, such as members of the Ericaceae family, which are generally adapted to more acidic conditions.

The relatively low diversity of these plant communities confuses the delineation between chance and deterministic community development. Soil nutrients, organic matter, and species diversity and evenness generally increased with community development, as is frequently seen during succession (Wali 1999; Jochimsen 2001; Hodkinson *et al* 2003). At MTSK and WG, the highest diversity was associated with the high levels of nitrogen, phosphorus, and carbon (Table 2.2). In contrast, the highest diversity and evenness values at UKHM corresponded to the most moderate organic and nutrient levels, the shrubland community. This occurrence provides support for Tilman's (1982, 1985) spatial resource theory of greatest heterogeneity, and thus diversity, in the most moderately productive systems. Similarly, Yarranton and Morrison (1974) found that diversity was greatest during the transition from the colonizing plant community to the more persistent species assemblage on the sand dunes of Grand Bend, Ontario: a process they suggested supports the organismal concept of vegetation. Thus, some central tenets of both holistic and spatial succession theory were demonstrated in this study. Unfortunately, the short time frame of this study provides only a snapshot of the extant plant communities. Mechanisms revealed, are those responsible for maintaining the current observed pattern and not necessarily those governing assembly and organization (Drake 1991). These can only be inferred.

Species dominance trends showed that the tailings were dominated by only a few species compared with surrounding habitats. With regards to enhancing succession on the tailings, Wali (1999) and Luken (1990) recommend emphasizing the quick establishment of only a few species thereby allowing additional species to invade naturally from external populations. Following this thinking, *Deschampsia caespitosa, E. angustifolium,* and *Carex aquatilis* are prime candidates for initial establishment. The inclusion of woody species such as *Salix* and *Populus* will increase diversity and create a more spatially (Collins and Wein 1998; Robinson and Handel 2000) and temporally (McLaren *et al* 2004) heterogeneous environment. To this end, a positive feedback will be initiated, and diversity on the tailings will be enhanced. Scarification of the tailings and the placement of debris on the tailings will also hasten community development.

Natural populations play an important role in ecosystem restoration. Maintaining diversity in adjacent ecosystems and improving tailings heterogeneity should be a management priority. This study has shown some species, which were found on the tailings and in surrounding ecosystems at each test site, possess a high colonization potential and could likely be enhanced with management. This initial establishment and subsequent natural succession would be enhanced by organic additions at all three sites three sites (e.g. compost) and at WG slow-release lime would also be very beneficial though the extreme acid generating potential of the WG tailings suggests that this will be a longer-term input unless plants are acid tolerant.

Study Two - Intrinsic metal tolerance in five Deschampsia caespitosa (L.) Beauv. populations from the Yukon Territory: implications for mine tailings revegetation

The frequent occurrence of metal tolerance in *D. caespitosa* in North America and Europe has most often been regarded as the result of local adaptation to elevated metal concentrations. However, it is still not fully understood whether the distribution of this species on many metal-contaminated sites is due to its inherent capacity to evolve metal tolerance *in situ* or whether there is intrinsic tolerance within the species. This study attempts to answer part of this question of intrinsic metal tolerance for *D. caespitosa* populations in the Yukon by testing the response of cloned seedlings from non-contaminated sites to potentially inhibitory levels of three toxic elements i.e. Ni, Zn, and Cd and comparing their performance with that of cloned seedlings from contaminated mine sites in the Yukon.

Materials and Methods

Collection and Maintenance of Plant Material

In August 2003, seeds of *D. caespitosa* were collected from a minimum of 30 individuals from each of three mine sites (United Keno Hill Mine, Mount Skukum, Wellgreen) and from two uncontaminated sites (Kluane Lake, Mayo Beach) in the Yukon Territory. Plants were initially grown in BM6 soilless medium and fertilized once a week with a 1/10 Arnon and Hoagland's solution (Hewitt 1966). A minimum of 60 individuals from each population were maintained in 4" plastic pots for 3 months in the greenhouse prior to metal tolerance trials in hydroponic solution.

Soil Sampling and Analysis

Soil samples were taken from the rooting zone of *D. caespitosa* and sent to Trent for analysis. Refer to Study One for methods and results (Tables 2.1 and 2.2).

Tolerance Tests

Three metal treatments were selected for hydroponic metal trials based on the ICP-OES analysis of Yukon mine tailings. Critical concentrations of nickel and cadmium were selected based on a preliminary trial experiment (the selected concentration caused at least a 50% reduction in root growth of one population). The critical concentration for zinc was chosen based on extensive literature. The metal concentrations and salts used were: Zn (20 ppm $ZnCL_2$), Ni (0.3 ppm $NiCl_2{\cdot}6H_2O$), and Cd (0.05 ppm $CdCl_2{\cdot}21/2H_2O$). The hydroponic growth medium was a 1/20 Arnon and Hoagland's solution (Hewitt 1966). The solution pH adjusted to 5.5 with NaOH and HCl. As determined by experiments on the linear rate of root growth in *D. caespitosa*, trials were run for 10 days.

Tolerance tests were conducted in 5 L acid-washed containers which were painted black to reduce algal growth and continually aerated. In the greenhouse (mean temperature 22˚C and mean R.H. 60% ± 10%), containers were placed in a split plot design: populations (5) x metal treatments (3+control) x replicates (10) and set at a 16 hrs (80 μmol m^{-2} s^{-1} photon flux density PAR) day and 8 hrs night cycle. Five even-sized and uniform tillers were placed in each container. Samples of metal-spiked hydroponic solution were taken at day 1 and 3 and assessed by atomic absorption spectrometry to ensure that metals were not adsorbing to the sides of the containers or being chelated by nutrient solution. Metal concentrations remained stable to the desired concentration during this time period. Thereafter, the hydroponic solution was replaced every 5 days to replenish nutrients and metals. After 10 days growth in the treatments, all plants were harvested and their root lengths measured.

In order to assess the metal-tolerance of *D. caespitosa* populations the root Tolerance Index (TI) (Wilkins 1957, 1978) was employed. A tolerance index was calculated based on the amount of root growth in the treatment compared with the root growth in the control: TI = (length of longest root in metal solution/ length of longest root in control solution) x 100.

Results

Tolerance Tests

Figure 3.1 summarises the data, expressed as average tolerance indices, for all populations in each treatment. For each metal treatment, plants can be placed into two discrete groups. First, those which possess some degree of metal tolerance; and second, those which had a tolerance index over 100% or 1 (i.e. the roots grew better in the presence of a potentially toxic exposure to the metal than in its absence). All five populations demonstrated a relatively high degree of tolerance, even those collected from non-contaminated sites and Mount Skukum whose tailings were not elevated in any of the three test metals. For the Ni and Zn tests, Kluane was the only population which did not have a tolerance index at or above 100%. Kluane seedling roots, however, still performed on average at 90% growth in Ni treatments and to 95% in Zn treatments relative to the control treatment. In the Cd treatments, neither Kluane (78%) nor Mount Skukum (81%) had tolerance indices at or above 100%. There was no significant difference found among populations in the Ni ($p=0.333$), Zn ($p=0.081$), and Cd ($p=0.275$) treatments.

Figure 3.2 illustrates the average absolute root growth for all populations under all treatments. There were significant differences found in the control treatments with regards to root growth ($p\leq0.001$) whereby Kluane had a significantly higher absolute root growth compared to Mayo ($p\leq0.001$). United Keno Hill ($p\leq0.001$), and Wellgreen ($p=0.003$). In the control solution, Mount Skukum had the second greatest root growth: significantly greater than that of Mayo ($p=0.002$) and United Keno ($p=0.015$). In the nickel ($p\leq0.001$), zinc ($p\leq0.001$), and cadmium ($p=0.001$) treatments there were significant differences in root growth among populations. Absolute root growth of Kluane in the nickel treatment was significantly greater than root growth of Mayo ($p\leq0.001$) and United Keno Hill ($p=0.001$). Mayo root growth was significantly less than Kluane ($p=0.001$), Mount Skukum ($p=0.002$) and Wellgreen ($p=0.002$) when zinc was present at potentially toxic concentrations in hydroponic solution. Relative to the control, Mount Skukum, United Keno Hill, and Wellgreen experienced an increase of root growth in the zinc treatment. Cadmium treatments resulted in a significant difference between Kluane and Mayo ($p=0.037$).

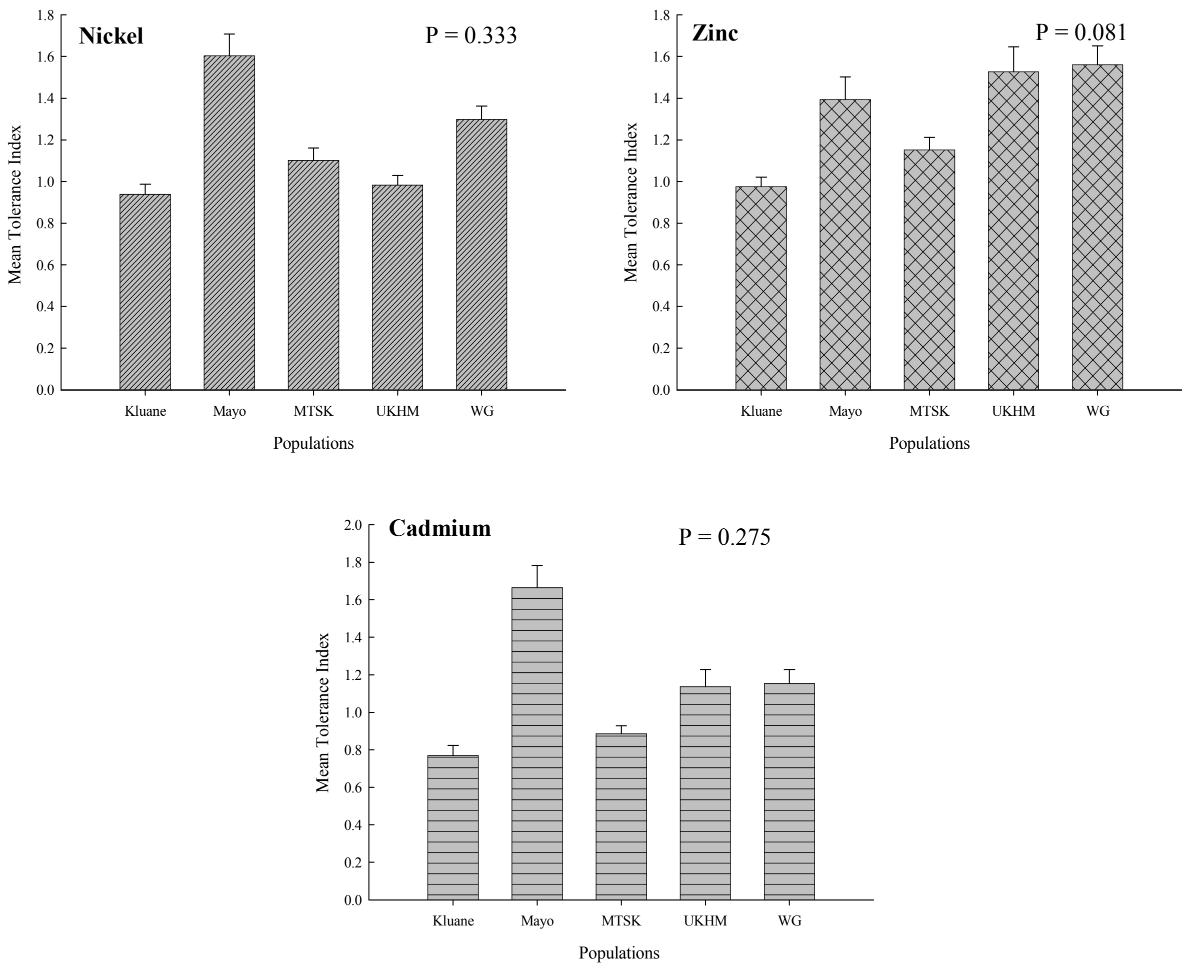

Figure 3.1 Mean tolerance Indices (5) of all *Deschampsia caespitosa* populations from the Yukon to nickel (0.3 ppm), zinc (20 ppm), and cadmium (0.05 ppm) where a value of 1 would suggest a perfect tolerance. Mount Skukum (MTSK), United Keno Hill (UKHM), and Wellgreen (WG) are mine tailings populations while Kluane and Mayo are populations collected from uncontaminated sites. Bars represent the standard error.

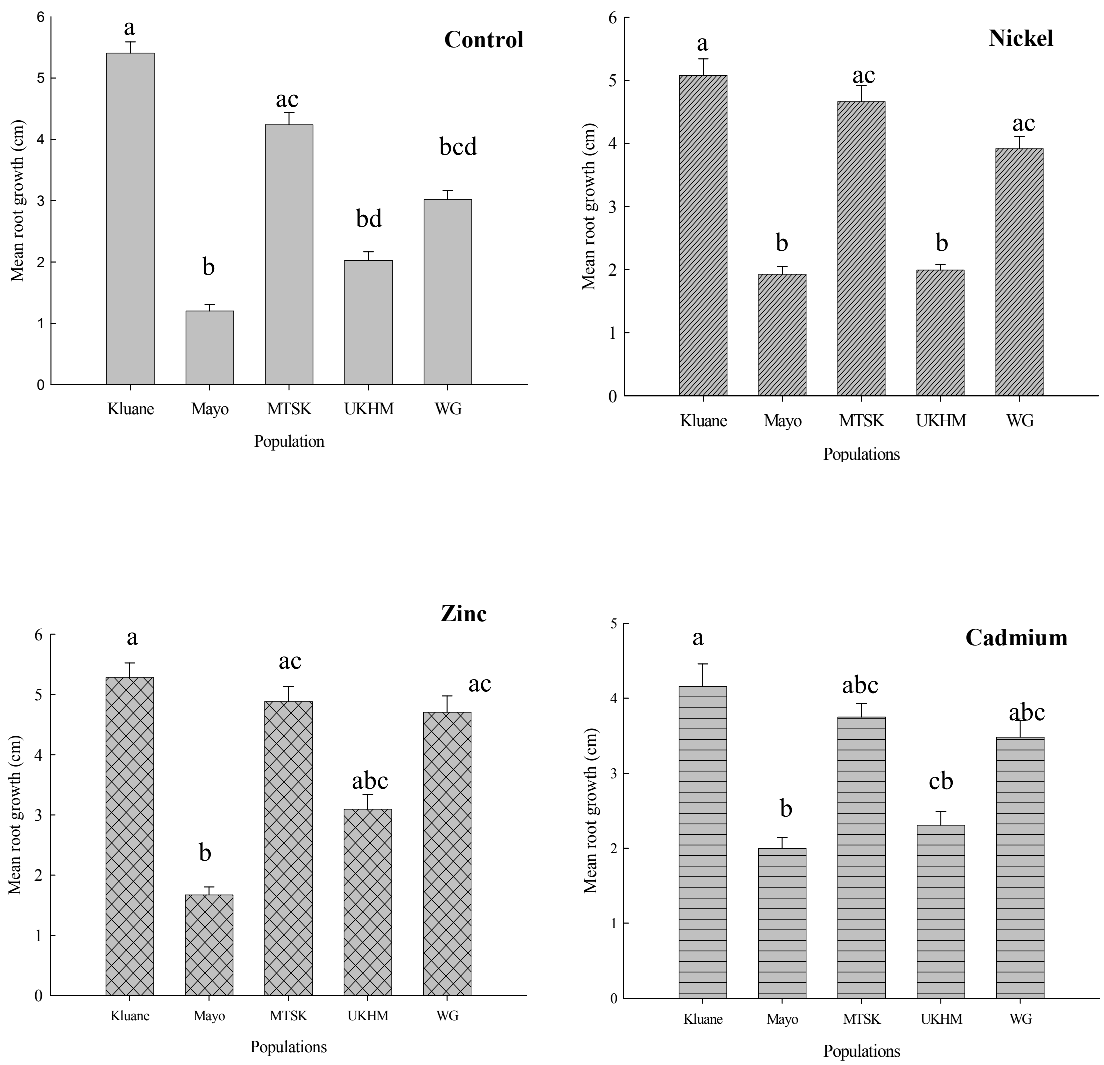

Figure 3.2 Mean root growth (cm) of *Deschampsia caespitosa* populations from the Yukon in control solution, nickel, zinc, and cadmium. Mount Skukum (MTSK), United Keno Hill (UKHM), and Wellgreen (WG) are mine tailings populations while Kluane and Mayo are populations collected from uncontaminated sites. Different letters indicate significant differences (P≥0.01) of average root length based on Tukey Test following a 1-Way ANOVA. Standard error bars are shown.

Discussion

The extensive work conducted on metal tolerance in plants has largely shown that the nature and degree of tolerance is determined by specific soil conditions, especially their metal content and that metal tolerance is typically metal specific (Jowett 1958; Gregory and Bradshaw 1965). This experiment examined five populations of *Deschampsia caespitosa* from sites ranging widely in nickel, zinc, and cadmium concentration. The critical test metal concentrations selected in this study, as well as lower metal concentrations used in other researchers' studies, have proven to be phytotoxic and substantially hinder root growth of non-tolerant populations of *D. caespitosa* (Von Frenckell and Hutchinson 1993; Cox and Hutchinson 1980; Baker *et al* 1986), as well as of other species such as *Agrostis tenuis* (Jowett 1958; Gregory and Bradshaw 1965), *Festuca ovina* (Gregory and Bradshaw 1965), *Agrostis gigantea* (Hogan and Rauser 1979), *Alyssum maritimum* (Schickler and Caspi 1999), and *Silene vulgaris* (Paliouris and Hutchinson 1984). Accordingly, the test concentrations of these metals used in these experiments can be regarded as relatively high compared to other published work and be expected to at least hinder root growth in non-tolerant individuals.

Figure 3.1 shows no significant population difference in response to all three test metals. Because the selected critical concentrations can be considered high and a diluted nutrient solution was used, I believe that these five Yukon populations all possess a remarkably high degree of tolerance to the test metals. These results demonstrate that metal tolerance in these Yukon populations of *D. caespitosa* is neither soil nor metal specific; rather it is intrinsic (Table 3.2).

Comparable results have been observed in the grass *Agrostis tenuis*. Jowett (1964), McNeilly and Bradshaw (1968), Walley *et al* (1974), and Gartside and McNeilly (1974) have all found some Pb, Cu, and/or Zn tolerant individuals of *A. tenuis* in normal populations and from these individuals, fully metal tolerant clones were often obtained in one or two generation(s). These studies are regarded as important portrayals of the rapid evolution of metal tolerance by natural selection, but have also lead to discussion of possible intrinsic metal tolerance within the species. In light of this, both the nature and degree of tolerance in the normal populations of *D. caespitosa* seen in this study are, in general, greater than that seen in the aforementioned studies of *A. tenuis*. Similar demonstrations of elevated metal tolerance are typically only found in plants classified as metallophytes, such as *Alyssum betolonii* (Morrison *et al* 1980), *Thlaspi goesingense* (Reeves and Baker 1984), *Calochortus sp.* (Fiedler 1985), and *Senecio sp.* (Reeves *et al* 1999) on serpentine soils; *Arabidopsis halleri* (Bert *et al* 2000) on calamine soils; and in *Thlaspi caerulescens* (Assunção *et al* 2003) which can be found on serpentine, calamine, and non-metalliferous soils (Reeves and Brooks 1983). The results of this present study demonstrate that a high degree of intrinsic tolerance to Ni, Zn, and Cd exists in the Yukon populations of *D. caespitosa*. In earlier Ontario studies, the control *D. caespitosa* populations did not show a general degree of metal tolerance, though a few individuals were indeed pre-adapted (Cox and Hutchinson 1979).

Intrinsic metal tolerance in these *D. caespitosa* populations may well be the result of a common metal tolerant Yukon ancestral population which has naturally colonized both contaminated and uncontaminated sites. Bush and Barrett (1993) showed that the populations of *D. caespitosa* which have invaded mine contaminated soils and tailings in Sudbury and Cobalt, Ontario, these sites being 175 km apart, have had separate origins and in both locations an local ancestral population has never been documented despite vigorous efforts to find such. It is very possible that the colonizing seeds have been transported by railway, wagon and truck from a population at the port of Little Current, on Manitoulin Island in coal shipments made over many years to the smelters in Sudbury, and earlier to the Cobalt mines. A similar dispersal mechanism may be responsible for the metal tolerance in the Yukon. Metal ore has been transported throughout the Yukon by rail, truck and boat for nearly 100 years. In fact, ore from United Keno Hill was historically taken by horse driven wagon and loaded on to ships at the Stewart River in Mayo, only kilometres away from where seeds used in this study were collected. During the over 70 years of mining at United Keno Hill mine it is probable that some human driven seed dispersal occurred between the mine site and loading docks, some 60 km away.

Intrinsic tolerance may also be explained by the general ecology of the species. The Yukon populations originate from ecosystems which are spatially and temporally heterogeneous (see Study One), particularly with regards to water table fluctuations. All sites are seasonally flooded. Flooded soils are typically anaerobic, but the rhizosphere itself may be aerobic and oxidized through the roots (Matthews *et al* 2004). Metals in the rhizosphere would therefore be mobilized under the aerobic conditions and relative to drier upland soils, plants would be exposed to higher metal concentrations. In turn, this could lead to intrinsic tolerance in some species which inhabit these environments (Doyle and Otte 1997).

The mechanisms of tolerance in *D. caespitosa* have not been well studied. Schultz and Hutchinson (1988) assessed the potential role of thiol-rich proteins (metallothioneins) in the copper tolerance of *D. caespitosa* from Sudbury, Ontario and concluded that this is an unlikely key mechanism for copper tolerance in this species. Other work has shown that Cu tolerant populations of *D. ceaspitosa* have less inhibited root phosphatase activity in contaminated environments compared to non-tolerant races (Cox and Hutchinson 1980a). This enzyme, therefore, may elicit some degree of copper tolerance. No work, to my knowledge, has examined the potential role of phytochelatins in the metal tolerance of *Deschampsia caespitosa* though the presence of phytochelatins may well be the key to *D. caespitosa* multiple metal tolerances at Sudbury, as it has turned out to be for a number of other species such as *Agrostis gigantea*, *Silene cucubalis*, and *Mimulus guttatus* (Steffens 1990; references therein).

There is growing evidence that phytochelatins (PC) are essential for normal constitutive tolerance. The capacity for PC production is thought to be present in all higher plants (Schat *et al* 2002) and a number of metals and metalloids such as Cd, Pb, Zn, Ni, Cu, and As have been shown to induce PC synthesis (Grill *et al* 1987). Cadmium, Pb, and Zn are considered the strongest PC elicitors by Steffens (1990), while in a recent study on PC induction in chickpea (*Cicer arientum*) plants were exposed to 6 different heavy metal ions i.e. Cd, Ni, Co, Zn, Cu, and As and of these only Cd, and As stimulated PC and homophytochelatin synthesis in the roots (Gupta *et al* 2004). *D. caespitosa* populations in Ontario (Cox and Hutchinson 1979) and Europe (Von Frenckell and Hutchinson 1993) have demonstrated tolerance to all of these metals, including simultaneous tolerance. The Yukon populations tested in this study also exhibited high tolerance to both Cd and Zn. PCs, therefore, may be playing a key role in this metal tolerance. This role, however, is likely only an immediate and general tolerance mechanism. PC production reduces glutathione levels and can result in oxidative stress (De Vos *et al* 1992), suggesting it would be costly to maintain this tolerance mechanism for the lifetime of this long-lived perennial grass. Ni is not considered as strong a PC elicitor as Zn or Cd and Ni-PC complexes are relatively unstable (Steffens 1990). Ni tolerance may have more to do with detoxification by low molecular weight chelators such as citrate and free histadine (Snager *et al* 1998). The mechanisms eliciting tolerance in this species and in particular the Yukon populations, will be the subject of further investigation.

It is well known that *D. caespitosa* contains a wide range of morphological and cytological variation (Kawano 1963). Lawrence (1945) demonstrated that *D. caespitosa* ecotypes exhibit: 1) individual and racial responses under uniform conditions; and 2) environmentally-induced responses when one individual is compared in different environments, for both physiological and morphological traits. Root production is an important morphological characteristic for tailings revegetation as roots help anchor plants and immobilize soil particles. Heavy metals as well as aluminium characteristically reduce root growth, especially in germinating seeds. Therefore, absolute root growth in the presence of heavy metals is a useful screening metric.

Figure 3.2 shows significant difference in absolute root elongation among populations within each treatment. In the presence of nickel, the Kluane Lake seedlings showed significantly greater absolute root growth ($p<0.01$) relative to United Keno even though United Keno had a higher average tolerance index. Field trials which were conducted in the Yukon mine sites in 2003-04 have involved seedlings and clones from the same experimental populations used in the present study. Transplants of *D. caespitosa* from the Kluane population significantly outperformed other populations in a Ni rich environment (see Chapter 4). In the hydroponic tests, Mount Skukum plants showed a higher absolute root growth in the Zn and in Cd treatments compared to United Keno, a population that originates from a Zn and Cd contaminated site (Table 2). In the field, Mount Skukum performed significantly better than United Keno transplants at United Keno Hill mine. Thus, while this present seedling root elongation experiment produced unexpected results, in that even uncontaminated sites had populations present with a high intrinsic metal tolerance, this phenomenon is not confined to a laboratory situation but has been repeated in the field.

The root growth results demonstrate a stimulatory response to the metals in solution whereby root growth in the metal treatment was frequently greater than that of the control (Figure 2). Tolerant individuals often show a stimulatory response in growth to essential elements such as Ni, Zn, and Cu (Antonovics *et al* 1971), and also for some non-essential elements such as Cd, As, and Pb (Baker and Walker 1989) followed at even higher concentrations by a reduction in root growth. Explanations for this positive occurrence may lie in theories such as the 'Metal Requirement Hypothesis'; however, evidence in the literature supporting this hypothesis is largely inconclusive (Harper *et al* 1997) and does not explain the tolerance demonstrated by *D. caespitosa* clones from the uncontaminated Yukon sites. The fundamental tenet behind this phenomenon may be better known when the mechanisms involved in tolerance are understood more fully.

Mine tailings typically represent an inhospitable environment for the (re)establishment of plants due, in large part, to overwhelming concentrations of heavy metals (Antonovics *et al* 1971). This study has demonstrated that all the Yukon test populations of *Deschampsia caespitosa*, including those from uncontaminated sites, exhibit a remarkable and unanticipated tolerance to a number of potentially toxic metals found within the three mine sites. While only five Yukon populations have been tested, an admittedly small number, the results give a strong indication that the Yukon populations possess an intrinsic metal tolerance which would enable all of them to be used for revegetation work. It suggests that the fact *D. caespitosa* has been one of the very few common invaders of these mine sites, may well lie in its intrinsic metal tolerance, but that its failure to substantially revegetate these sites to date may be due to additional site factors such as surface erosion, semi-arid climate, lack of organic matter, nutrient challenges and short growing seasons. In contrast, the invasion of *D. caespitosa* into the Sudbury mining area, commencing in 1973, now covers thousands of hectares.

Study Three - Revegetation of Yukon mine tailings sites and the initiation of natural plant colonization by Deschampsia caespitosa L. Beauv.

The objective of this study was to screen local and non-local, mine and non-mine populations of *Deschampsia caespitosa* at three abandoned mine sites in the Yukon Territory for their ability to survive and reproduce, as well as to test their *in situ* response to various soil amendments. The fact that *Deschampsia ceaspitosa* is naturally found in widely ranging habitats (Lawrence 1945; Kawano 1963; Ward 1969) suggests that all populations could be capable of establishing and reproducing on the tailings environment, though transplants and seedlings originating from local populations (ecotypes) would likely perform the best. The natural occurrence of *D. caespitosa* in nutrient poor habitats (Davy 1980) and the nature of low-nutrient requiring plants (see Chapin 1980) implies that these plants could be capable of growing in unamended tailings and that the application of nutrients (i.e. commercial fertilizer) would not provide a substantial benefit. Furthermore, the ability to intercept wind blown seeds and/or promote successive plant establishment, in addition to that of chance colonization, is important for long-term success and for the initiation of natural successional processes (see Yarranton and Morrison 1974). Therefore, the ability of *D. caespitosa* to act as a nurse crop and facilitate the colonization of additional plant species compared with chance colonization on bare tailings was also assessed. The results of this study will contribute to a revegetation programme at the three test sites, which remain largely unvegetated after abandonment some years ago, as well as other hard rock mine sites in northern environments where *Deschampsia caespitosa* is commonly found.

Methods

In June 2003, three mine sites in the Yukon Territory, Mount Skukum (MTSK), Wellgreen (WG), and United Keno Hill Mine (UKHM) were selected for experimentation from a number of candidate sites as they provided a wide range in physical and chemical conditions. Uncontaminated non-mine sites were selected based on a relatively low level of disturbance and the presence of *D. caespitosa*. Experimental plots were established in the three tailings areas during June 2003. Two blocks (replicates) were established for each treatment in an area with no existing vegetation. Four treatments were used at MTSK and UKHM: 1) no amendments (untreated); 2) compost; 3) fertilizer; and 4) compost and fertilizer (mixed). Compost was acquired from the City of Whitehorse. Enough compost was added to create a planting medium of at least 10 cm deep around the root system of transplants. A commercial pellet 7-7-7 (NPK) slow release fertilizer was used and applied at manufacturers recommended rates (300 kg/ha). Fertilizer was worked into the soil to a depth of 15 cm. Due to the very acidic nature of the WG tailings an additional treatment of lime was used at this site only. Thus, the five treatments used at WG were: 1) no amendment (untreated); 2) lime; 3) lime and compost (compost); 4) lime and fertilizer (fertilizer); and 5) lime, compost, and fertilizer (mixed). A commercial dolomite lime was used and applied at rate which in the short term corrected the pH from ~2.7 to ~5.5.

Healthy transplants of *D. caespitosa* were collected from each mine site and planted reciprocally at all sites and for all treatments. Transplants were also collected from two uncontaminated sites at Kluane Lake (Kluane) and Annie Lake Road (ALR) and planted in all treatments at each site. Each plot contained a minimum of four individual plants from each population. In addition to the Yukon plant populations, three additional clonal populations of *Deschampsia caespitosa* were brought to the Yukon. These plants were initially grown in the greenhouse at Trent University, Peterborough, Ontario to multiply the material. They were grown from seeds collected from two metal contaminated mine sites in Sudbury, Ontario (Coniston and O'Donnell Roast bed (RB)) and from an uncontaminated site in Indian River, Ontario (Taylors).

A relative scoring system for vegetative growth was created to assess the relative performance of transplants (Figure 4.1). Plants were scored at the end of the first growing season (2003) and again at the end of summer 2004. The vegetative scoring system was based on growth and visual health of the plants and is as follows: (0) dead; (1) poor growth with severe chlorosis and/or purpling and 3/4 die back; (2) better growth, but with severe chlorosis and/or purpling and 1/2 die back; (3) moderate chlorosis and/or purpling, little die back; (4) new growth, healthy; (5) lush growth without visual chlorosis or anthocyanin production (purpling foliage). The number of individual flowering stalks produced in summer 2004 was also recorded in early August.

Seed plots were established using the same design as the transplant plots: two plots per treatment, each containing 5 subplots (30 cm X 30 cm). For untreated and fertilizer treatments, a 1 m^2 area was scarified to create a seed bed. For compost and mixed amendment treatments, 1

m^2 plots were established and 5 cm of compost was added onto the tailings surface. In fertilizer and mixed plots, fertilizer was applied at a rate of 350 kg/ha, a common rate for seeding practices in the north (Kennedy 1993). Seeds were collected from a minimum of 30 individuals from each of the Yukon test site and from the Kluane reference site in August 2003. In each seed plot, 1 g of *D. caespitosa* seed (approx. 2000 seeds) per population was planted on top of the tailings/compost surface. In June 2004 the number of germinated seedlings in each subplot was counted. Surviving seedlings were counted again at the end of July 2004.

In August 2004, the presence and abundance of voluntary colonizers of other plant species was documented. This assessment was done in each 1 m^2 transplant and seed plot for each treatment at all sites. Two 1 m^2 control plots where nothing was seeded and/or transplanted and no soil amendments were added, were used to compare plant invasion. Because plots were placed in an area with no existing vegetation, the presence of other species can be assumed to have followed initial plot establishment.

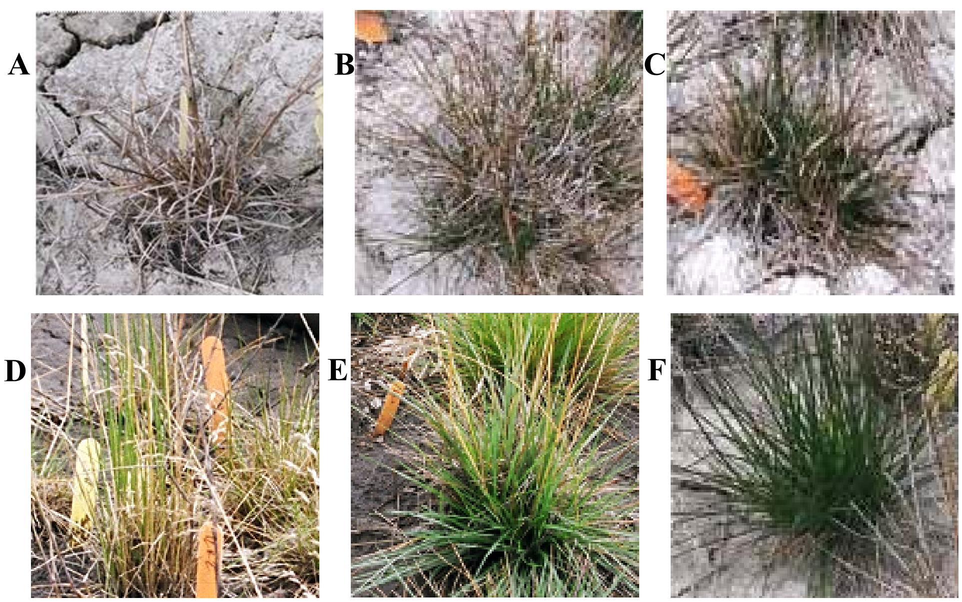

Figure 4.1 Sample pictorial description of Relative Vegetative Scoring System used to evaluate the performance of *Deschampsia caespitosa*. In the field, specimens were selected as representative of each classification and all other transplants were scored relative to these specimens: A) dead (0); B) poor growth with severe chlorosis and/or purpling and 3/4 die (1); C) better growth, but with severe chlorosis and/or purpling and 1/2 die back (2); D moderate chlorosis and/or purpling, little die back (3); E) new growth, minimal signs of stress (4); F) lush growth without visual chlorosis or anthocyanin production (purpling foliage) (5).

Results

Over-wintering of Sites

Spring snowmelt (2004) at Mount Skukum (MTSK) caused some minor damage to the experimental site. The seed plots were most affected while there was no apparent damage to transplant plots. There was severe water damage done to the Wellgreen (WG) plots during both summer 2003 and 2004. In 2003, unremitting rains caused the tailings pond to flood well above the high water mark and most transplant and some seed plots were covered with water. Plots closest to the pond may have, at times, been under more than 30 cm of water. As a result of this flooding, or possibly from snow melt in spring 2004, some plants were either buried or washed away. There was no disruption to plots at the United Keno Hill (UKHM) mine site.

Vegetative Growth in Revegetation Plots

Mount Skukum

2003 vegetative score data did not show significant differences among soil amendment treatments ($p=0.052$). In general, plants grown in the fertilizer treatment performed poorer than those in the other treatments (Figure 4.2). There were no clear populations effects ($p=0.160$). The 2004 relative performance scores did show significant treatment differences ($p \leq 0.001$) but again, no population effect ($p= 0.096$) (Figure 4.2). There was an overall decrease in scores from 2003, but excluding Wellgreen, individuals from all *D. caespitosa* populations survived the winter with minimal mortality, and subsequently grew during the summer of 2004. Plants in untreated plots performed significantly better than those in every other treatment ($p<0.05$); plants in compost and mixed amendment treatments performed better than fertilizer plots ($p<0.05$), and did not differ from each other. In general, the two local populations, Annie Lake Road (ALR) and MTSK plants performed significantly better than the remaining populations.

United Keno Hill

Vegetative growth at the time of recording in 2003 showed that treatment had a significant effect ($p=0.005$), but that population did not ($p=0.032$) (Figure 4.3). Plants grown in compost ($p<0.01$) and in mixed amendment ($p<0.05$) plots grew better than with the fertilizer amendment and generally better than in untreated plots. In 2004, significant differences were found in the relative scores for both treatment ($p \leq 0.001$) and population ($p \leq 0.001$) (Figure 4.3). Overall, scores decreased from 2003. All populations had surviving individuals in each treatment. Plants in untreated, compost, and mixed plots did significantly better than with fertilizer ($p<0.05$). The mean scores for growth of ALR, MTSK, and UKHM populations were significantly greater than all other populations ($p<0.05$). This repeated the pattern of 2003.

Wellgreen

For 2003, Kruskal-Wallis tests revealed a non-significant treatment effect ($p=0.325$), but a significant population effect ($p\leq0.001$). Overall, plants growing on the lime amendment performed the poorest (Figure 4.4). Kluane plants scored significantly higher values ($p<0.05$) than all other populations except for WG, which in turn, scored significantly higher than remaining populations except for the Sudbury RB population ($p<0.05$). Again in 2004, treatment revealed a non-significant effect ($p=0.134$) while a significant population ($p=0.001$) effect was found. Nonetheless, all populations tested had some surviving individuals for the first two years. As in the 2003 data, Kluane transplants significantly outperformed all populations, except for RB ($p<0.05$), which itself performed better than every other population apart from Coniston ($p<0.05$). The performance of WG transplants declined in 2004, but still outperformed MTSK, UKHM, and Taylors transplants ($p<0.05$). At WG, the two local populations and the two Sudbury area ones performed and survived the best.

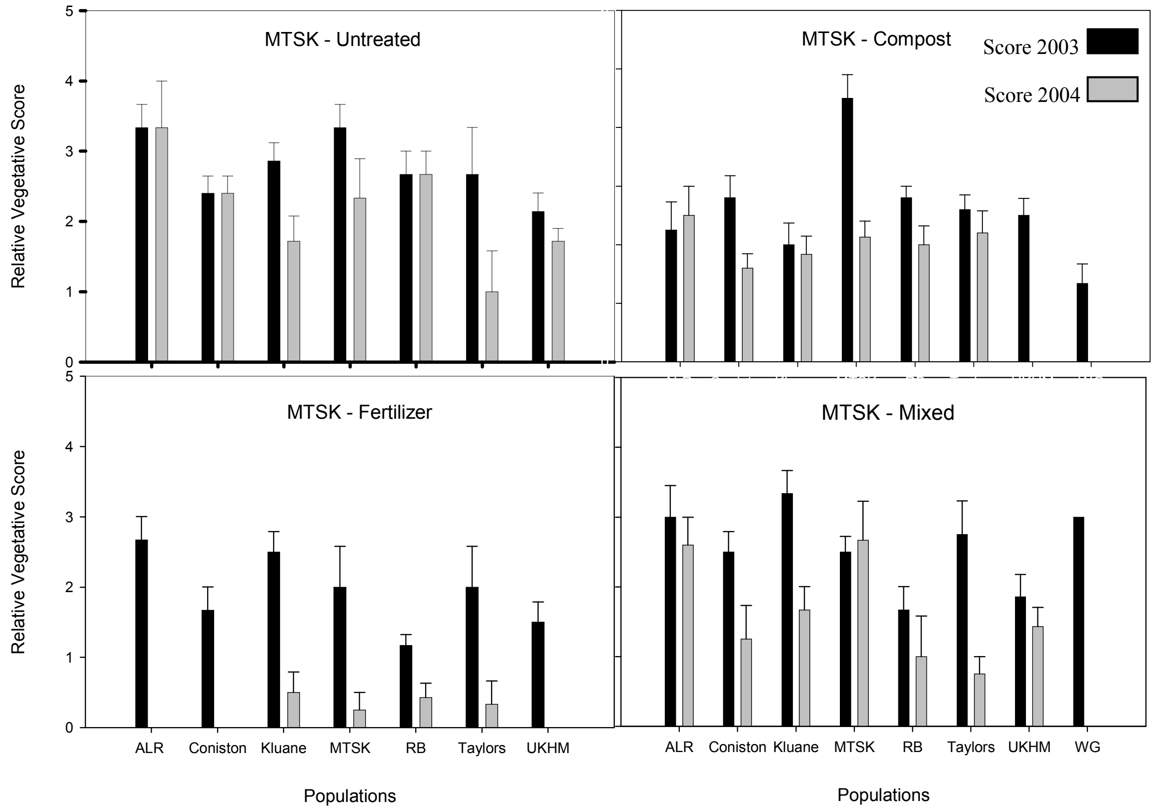

Figure 4.2 Mean relative vegetative scores (scoring ranged from 0-5) of *Deschampsia. caespitosa* transplanted from 8 sites for both soil amendment treatments and populations as assessed in August 2003 and 2004 at Mount Skukum mine. Bars represent standard error. The mixed amendment is the combination of fertilizer and compost.

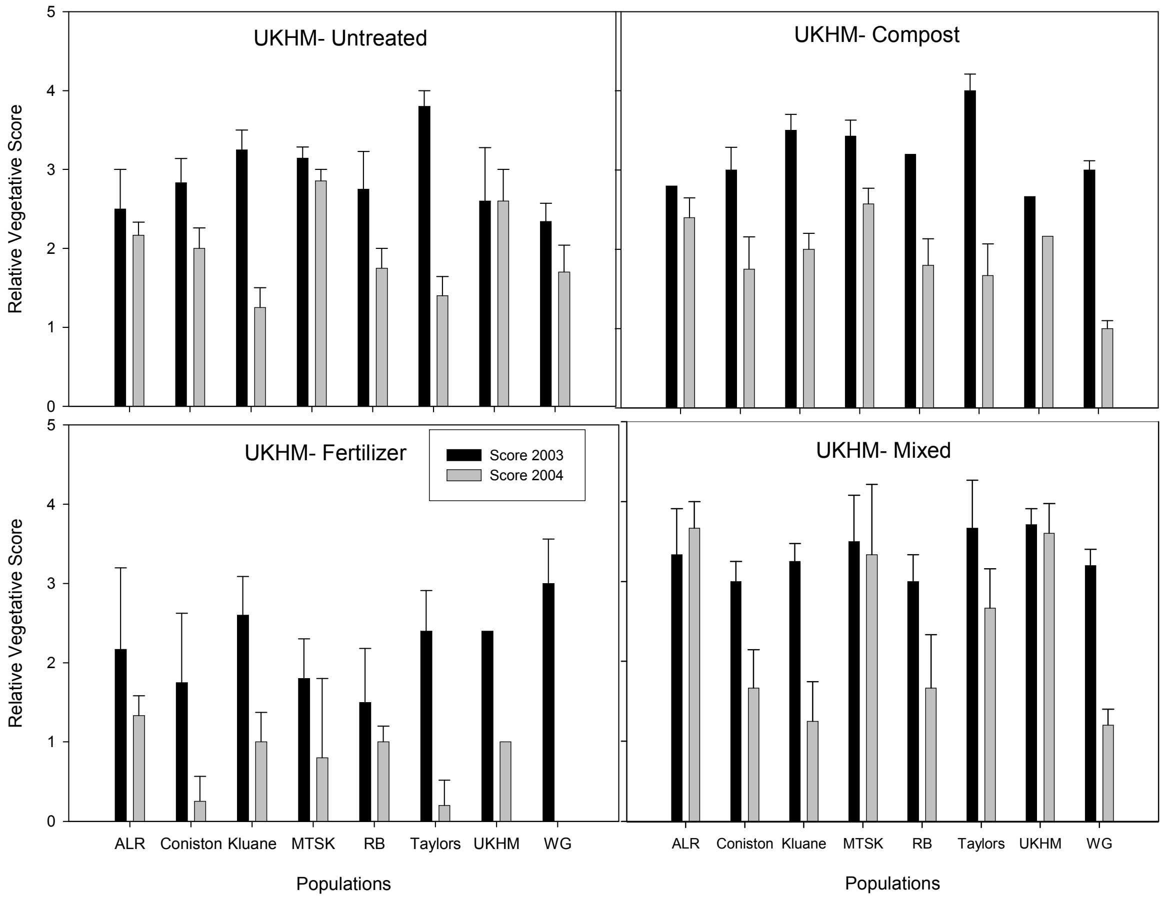

Figure 4.3 Mean relative vegetative scores (scoring ranged from 0-5) of *Deschampsia caespitosa* transplanted from 8 sites for both soil amendment treatments and populations as assessed in August 2003 and 2004 at United Keno Hill mine. Bars represent standard error. The mixed amendment is the combination of fertilizer and compost.

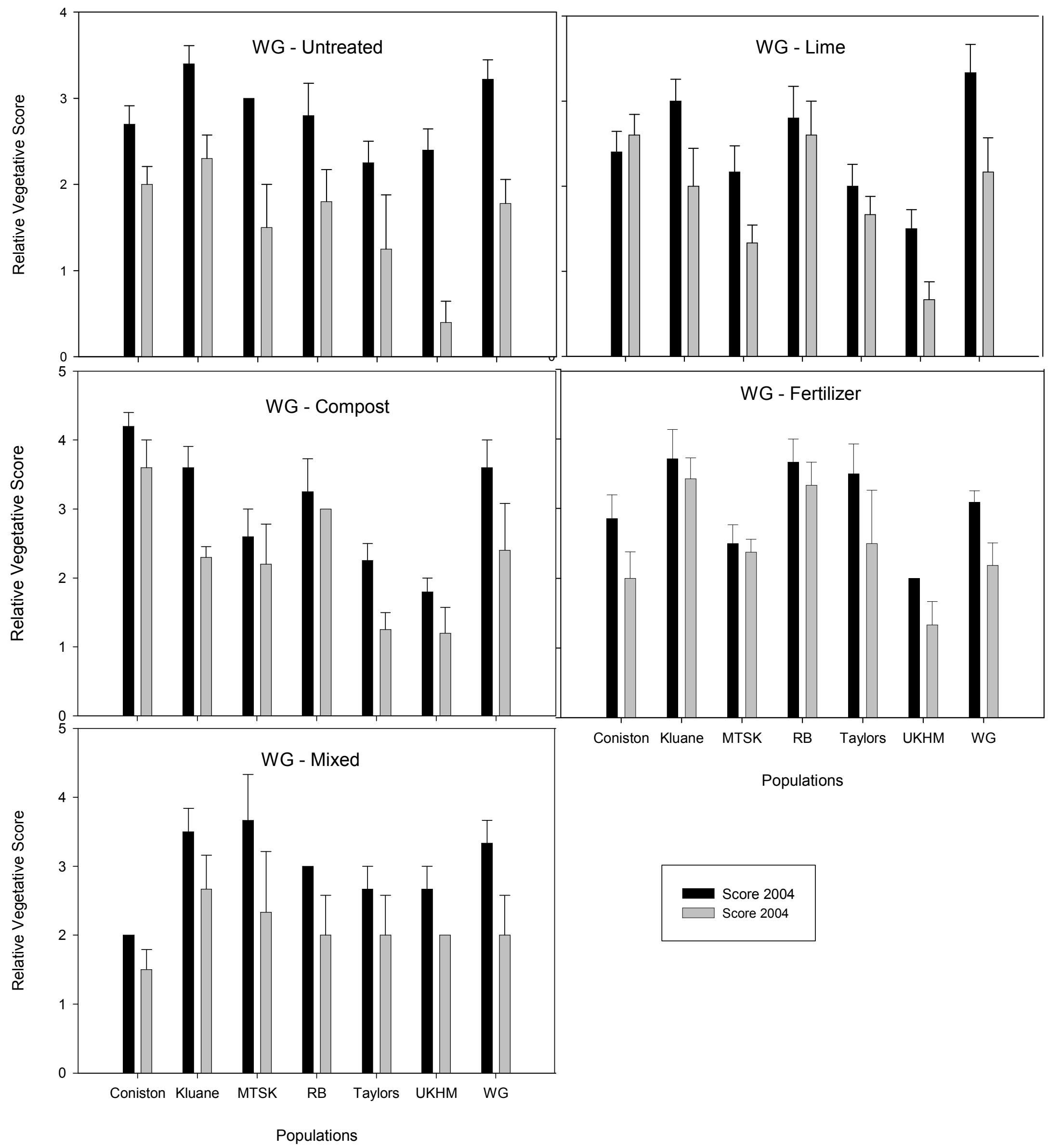

Figure 4.4 Mean relative vegetative scores (scoring ranged from 0-5) of *Deschampsia caespitosa* transplanted from 7 sites for both soil amendment treatments and populations as assessed in August 2003 and 2004 at Wellgreen mine. Bars represent standard error. All treatments, excluding untreated, were combined with enough lime that in the short-term increased the pH to 5.5. The mixed amendment is the combination of fertilizer and compost.

Floral Production

The number of flowers produced at MTSK was significantly affected by the treatments ($p \leq 0.001$), but did not differ significantly among populations ($p = 0.189$). The mean values for flower production of the *D. caespitosa* populations were, in fact, highest on the unamended tailings. The 7-7-7 fertilizer proved disastrous to flowering in all populations with no flowering at all (Table 4.1). Overall, ALR and MTSK produced the most flowers relative to other populations, reflecting their superior vegetative growth at this site.

Floral production at UKHM in 2004 revealed a significant treatment ($p \leq 0.001$) and population ($p = 0.014$) effect (Table 4.1). Plants grown in fertilizer plots did not produce any flowers. MTSK, ALR, and UKHM produced the largest number of flowers, paralleling the growth performance scores.

In regards to flowering at WG, transplants did not differ significantly among treatments ($p=0.054$) or populations ($p=0.061$) (Table 4.1). Unlike the response at MTSK and UKHM, however, plants grown in fertilizer plots at WG produced more flowers than the other treatments. Best overall flower production was achieved by Kluane and RB populations.

Seed Plots

The percent survival of seedlings differed among treatments and sites (Table 4.2). At MTSK, no seeds in any treatment or from any population germinated. At WG, there was no germination or survival in any untreated, lime, or fertilizer plots. However, WG compost plots had an average survival of 9.38%; mixed amendment plots had an average of 3.25%. In both treatments, Kluane and WG seedlings survived the best. At UKHM, seedling germination and survival were greater compared to the other sites. The compost treatment allowed the highest average survival (78.2%). Mixed amendment, untreated, and fertilizers plots had an average percent survival of 41.1%, 28.9%, and 20.7%, respectively. In terms of populations, Kluane had the greatest mean survival (54.9%), followed by UKHM (45.7%), WG (44.5%), and MTSK (30.6%). All populations were capable germinating and surviving under each soil amendment treatment at UKHM.

Table 4.1 Mean number of flowers produced in each treatment for transplants from 8 sites to 3 host sites in 2004 with standard error in parentheses. *Significant difference (P<0.05) among populations when treatments are pooled is shown. **Significant difference (P<0.05) among treatments when populations are pooled.

		ALR	Coniston	Kluane	MTSK	RB	Taylors	UKHM	WG	Mean(**)
MTSK	untreated	7.66	5.80	3.43	6.83	8.00	2.33	4.86	0	4.86 (a)
	compost	7.25	3.00	2.50	6.00	5.20	2.20	0	0	3.27 (a)
	fertilizer	0	0	0	0	0	0	0	0	0.00 (b)
	Mixed	9.00	0	3.33	6.33	0	0	0.86	0	2.44 (c)
	Mean(*)	5.98	2.20	2.32	4.79	3.30	1.13	1.43	0	
UKHM	untreated	4.33	3.67	1.50	3.71	0.80	3.40	4.40	0	2.73 (a)
	compost	10.80	0.75	2.00	10.14	2.80	0	9.67	0	4.52 (a)
	fertilizer	0	0	0	0	0	0	0	0	0.00 (b)
	Mixed	21.67	1.67	4.25	24.33	6.00	2.33	13.60	0	9.23 (c)
	Mean(*)	9.20 (a)	1.52 (b)	1.93 (b)	9.54 (a)	2.40 (b)	1.43 (b)	6.91 (a)	0	
WG	untreated	.	1.90	8.75	0.00	9.00	0.75	0.60	4.56	3.65
	Lime	.	6.80	3.33	1.33	8.40	1.33	1.83	2.83	3.70
	compost	.	19.20	10.20	5.60	4.00	0.75	5.00	5.40	7.16
	fertilizer	.	2.29	20.00	6.50	11.67	7.33	1.00	9.27	8.29
	Mixed	.	1.25	14.67	8.33	7.33	6.33	10.33	4.67	7.56
	Mean(*)	.	6.29	11.39	4.35	8.08	4.12	3.75	5.34	

Note: Non-mine sites: ALR: Annie Lake Road; Kluane, Taylors: Mine sites: Coniston, Roast Bed (RB), Mount Skukum (MTSK), United Keno Hill (UKHM), Wellgreen (WG).

Table 4.2 Mean percent survival of *D. caespitosa* seedlings at all mine sites. Seeds were planted at the end of 2003 and the number germinated was recorded in June 2004. The number surviving in August 2004 were recorded and percent survival is calculated on the number surviving as a proportion of those which actually germinated. Standard error is shown in parentheses.

		Untreated (%)	Lime (%)	Compost (%)	Fertilizer (%)	Mixed (%)
UKHM	UKHM	31.2 (2.1)	.	91.4 (7.7)	33.8 (11.1)	26.3 (8.1)
	MTSK	17.5 (5.2)	.	54.5 (20.1)	10.8 (2.5)	40.0 (1.45)
	WG	30.3 (1.2)	.	66.6 (13.9)	19.0 (5.1)	62.2 (21.3)
	Kluane	36.6 (1.6)	.	100.0 (0)	19.1 (10.7)	63.9 (16.7)
MTSK	UKHM	0	.	0	0	0
	MTSK	0	.	0	0	0
	WG	0	.	0	0	0
	Kluane	0	.	0	0	0
WG	UKHM	0	0	0 (0)	0	0 (0)
	MTSK	0	0	4.2 (10.4)	0	0 (0)
	WG	0	0	14.7 (5.6)	0	9.6 (10.7)
	Kluane	0	0	18.6 (7.5)	0	3.3 (1.6)

Invasive Colonizing Plants

The plant species which have colonized both transplant and seed plots varied among sites (Table 4.3; Appendix B). At MTSK, there were no colonizing plants recorded in or around the transplant plots of any treatment. In the seed plots, untreated and fertilizer plots also had no colonizers. Compost and mixed plots, however, had an average species richness of 7 and 6, respectively. Most of the species documented in the plots were not found growing naturally in the mine vicinity. Thus, the compost itself contributed seeds. There was no plant invasion in control plots. There was extensive colonization in both transplant and seed plots at UKHM (Table 4.3). There was a total of 12 additional plant species which colonized all transplant plots from the time of establishment in June 2003 to August 2004 (Appendix B). A total of 14 species were documented colonizing the seed plots. Compost and mixed amendment plots contained plant species which were not found in adjacent areas such as *Polemonium pulcherrium*, *Polygonum aviculare, Matricaria matricariodes*, *Capsella bursa-pastoris, Chenopodium album,* and *Lepidium densiflorum*. The control plots had voluntary invasion by 3 species.

There was minimal colonization of the WG transplant plots: only 3 additional plant species were present in plots (Table 4.3; and Appendix B). Seed plots, however, had a species richness of 8. There were no invaders in either untreated or lime plots, and only one invading individual in fertilizer plots. Compost plots and mixed amendment plots had a species richness of 7. This included *Matricaria matricariodes*, which was not found in the WG area. Control plots had one voluntary invader.

Table 4.3 Mean number of plants by treatment, which have invaded the transplant and seed plots at each of the three mine sites (Mount Skukum (MTSK), United Keno Hill (UKHM) and Wellgreen (WG) following initial plot establishment. Values are the mean of the two subplots per treatment irrespective of plant species; however plant species are listed in Appendix B. The lime treatment was only present at Wellgreen. Control plots had no amendment of scarification and were located adjacent to experimental plots.

	Transplant Plots				Seedling Plots		
Treatment	**MTSK**	**UKHM**	**WG**		**MTSK**	**UKHM**	**WG**
untreated	0	71	0		0	15.5	0
Lime	.	.	1.5		.	.	0
compost	0	69	5		77	70	12.5
fertilizer	0	40	0.5		0	10.5	0.5
Mixed	0	30	3.5		71.5	40.5	9.5
control	0	13	0.5		0	13	0.5

Discussion

The spread of contamination at abandoned mine tailings sites is responsible for the degradation of human establishments, ecological systems, and agricultural lands (Bradshaw and Chadwick 1980; Tordoff *et al* 2000). Grasses are useful in stabilizing mine tailings as their root systems retain soil better than the roots of forbs or woody plants (Luken 1990; Helm 1995). Mathematical models suggest that patches or buffers of grass could reduce sediment loss by up to 25% and full cover could reduce erosion by more than 70% compared with that from bare tailings (Lambert *et al* 1999).

The results of this present study demonstrate that, as predicted, transplants of Yukon and Sudbury area populations of the native grass *Deschampsia caespitosa* are capable of establishing and reproducing in each of the tested mine sites irrespective of soil amendment and even in unamended tailings during the first two years of data collection. Local populations performed the best at both MTSK and WG also as predicted. In contrast to the prediction, however, the top performing populations at UKHM were not local to the site. Instead, the two populations from the MTSK region i.e. Mount Skukum (MTSK) and Annie Lake Road (ALR) attained the highest relative scores. Seeds of *D. caespitosa* populations from several locations of origin were capable of germinating and surviving even in unamended tailings and despite hot and extremely arid conditions. Further, the physical presence of these plants, as well as the addition of soil amendments, encouraged the natural invasion of plant species from adjacent habitats relative to chance colonization. Thus, the use of *D. caespitosa* in a revegetation programme at the tested sites, and likely at other tailings sites in the north, will contribute to a low input management approach. Of course, these trials need to be extended over several years to determine that their success is long-term.

Within many areas of the Yukon Territory, the summer of 2004 brought about the warmest and driest summer conditions on record: reaching 36˚C in the city of Whitehorse during the month of June and experiencing drought for more than 6 weeks. Fires burned for many weeks around Kluane and Dawson. Hot and dry weather impedes plant growth and establishment (Walker and Powell 2001) and these climatic conditions likely contributed greatly to the decline in relative scores from 2003 to 2004. Under such climatic conditions, organic matter becomes vital in the development of plant communities (Walker 2003). Hass and Kuser (2003) found that organic mulch and organic mulch combined with slow-release fertilizer significantly improved the establishment of *Chamaecyparis thyoides* in an extremely low-nutrient sandy site on the Atlantic

Coastal Plain of the United States. This effect was repeated at United Keno Hill both in transplant and seed plots and to a lesser, but still significant extent at Mount Skukum, and in general at Wellgreen (Table 4.4).

Other forms of organic matter have improved plant cover in northern resource extraction sites. Sewage sludge from camp facilities in the Kuparuk Oilfield in Alaska improved plant growth relative to plots amended with commercial fertilizer (Bishop *et al* 2000; as cited in ABR 1995) and has shown promise as an amendment for kimberlite and gold mine tailings revegetation in the Northwest Territories (J. Kidd, pers. comm.). Human night soil from the mine facilities at Wellgreen was dumped in the southwest corner of the tailings impoundment during the mid-1980's and this corner is the only area of the tailings where substantial natural colonization has occurred. This natural colonization included *D. caespitosa*. Topsoil additions have also been successfully used for revegetation. Topsoil, that was obtained from nearby land or collected and stockpiled prior to mining, increased plant cover and productivity compared to plots where no topsoil was added (Walker and Powell 2001; Zhang *et al* 2001). Topsoil is a source of nutrients. It also contains microorganisms that could aid in the establishment of nitrogen-fixing plant species or mycorrhizal relationships and may act as a seed bank for native local seeds. Regrettably, topsoil is limited at most mine sites in the north due both to slow decomposition rates and a lack of prudence by some mine operators. The ability of *D. caespitosa* to grow and reproduce in the unamended tailings, therefore, provides a valuable option for Yukon restorationists and land managers.

The difficulty in attaining large quantities of organic mulch for revegetation in the north has led to a high reliance on commercial fertilizer. Commercial fertilizers increase soil nutrient status and often facilitate rapid establishment of cover on disturbed soils. Mougeot Geo Analysis and S.P. Withers Consulting (2000) found that seedling establishment at five mineral exploration sites in the Yukon was enhanced by commercial fertilizer, alone and in combination with other soil amendments such as microbial inoculants, topsoil, and straw. Long-term success was greatest in plots containing topsoil, though topsoil by itself was not tested.

Commercial fertilizer, unfortunately, only offers a short-term response and alone is not a management solution. Rapid decline and high mortality was seen in plants grown in fertilizer plots at Mount Skukum (Figure 4.2) and United Keno Hill (Figure 4.3). Decreases in plant productivity on mine tailings over time is frequently seen in without additional amendments of fertilizer (Kidd and Jorgenson 1992) as fertilizer is used by plants and rather than cycled becomes tied up in undecomposed litter and soil organic matter (Nadelhoffer *et al* 1992) or is leached due to the sandy texture of tailings (Piha *et al* 1995). In addition, fertilizer also has a tendency to over-stimulate herbaceous growth and cause low root:shoot ratios thereby leading to severe moisture stress in plants (Walker 2003) and has also been shown to increase metal accumulation in aerial plant parts compared to less nutrient rich amendments (Dueck *et al* 1987).

The adverse response to fertilizer demonstrated in this study may suggest that these plants, which often associate with lower nutrient environments (see Study One) experienced some degree of fertilizer burn. By the end of summer 2003, the relative scores of plants growing in fertilizer plots at Mount Skukum and United Keno Hill were, on average, lower than those in the other treatments. This was amplified in 2004. The rate of fertilizer applied in this study was less than used in many other northern revegetation projects (Kennedy 1993; Hill *et al* 1996; Withers 1999) and a slow release-fertilizer was used. Other northern revegetation projects, however, have used agronomic species, which have been bred for fast growth and rapid response to nutrient application (Chapin 1980). In addition, fertilizing rates can be sensitive to site specific substrate composition and thus the discrepancy between nutrient supply and toxicity may be delicate. Kozlov and Haukioja (1999) found that fertilizer used to enhance the establishment of mountain birch (*Betula pubescens*) in the heavy metal contaminated industrial barrens of Kola Peninsula, Russia caused rapid death of seedlings. They suggested this impact may have arisen from phosphate-enhanced toxicity; though, the same fertilizer rates have improved woody plant established in industrial barrens around Sudbury, Ontario: an environment with similar physio-chemical conditions. While it is evident that the appropriate rate of fertilizer needed at Mount Skukum and United Keno Hill was not established, commercial fertilizer was not necessary for the short-term establishment and growth of both local and non-local populations of *D. caespitosa*. Thus, if the goal is to initiate natural colonization rather than rapidly establish full vegetative cover, fertilizer is likely not needed for long-term community development.

In contrast, plants grown in fertilizer plots at the strongly acidic Wellgreen site scored higher than those grown in the other soil amendment treatments (Figure 4.4; Table 4.4). The site specific factors of Wellgreen tailings may be such that N-P-K fertilizer substantially improves growing conditions for *D. caespitosa*. Fertilizer has considerably improved the growth of *D. caespitosa* seedlings in Sudbury, Ontario tailings which, like Wellgreen, are very acidic (pH~3.5) and elevated in Ni, Cu, Fe, and Al (Bagatto and Shorthouse 1999). Thus, the combination of high acidity and elevated heavy metal composition may be conducive to a positive fertilizer response.

Unlike Wellgreen, however, Winterhalder (1981) found that the mere application of crushed lime facilitated deliberate plant establishment as well as initiated spontaneous colonization in Sudbury mine sites. The July 2003 flood may have dissolved and diluted a large portion of the fertilizer as well as the lime, reducing it to a much lower level that that initially applied. The positive response may be due to benefits of a very low level of fertilization whereas at United Keno Hill and Mount Skukum the negative results may be due to too high a dosage, which was not inadvertently reduced by flooding.

Seed production and dispersal of viable seeds by sexual reproduction is critical for long-term plant community sustainability. In this study, transplanted individuals from multiple populations demonstrated an ability to reproduce sexually *in situ* (Table 4.1). Seeds produced by these plants were viable since clones grown from these seeds were used in greenhouse experiments and these seeds were also sown and germinated in the field, though the precise germination viability was not tested. Viable seed, particularly in populations which have shown survivability and good performance in field trials, permits seed collection for additional revegetation work. The production of viable seed also suggests a high colonization potential in this species.

Colonizing ability is important in the early stages of both natural and directed community development. Pywell *et al* (2003) found that in the few years following restoration of grassland, successful plants had a high colonization ability. These plants were good competitors, produced viable seed, relied on vegetative growth and a seed bank for reproduction, and were habitat generalists. Williams (1983) has shown both early and late shed seeds of *D. caespitosa* have a high level of viability, and of these viable seeds, there is a high degree of germinability as well as the presence of a delayed dormancy mechanism. This suggests that *D. caespitosa*, a habitat generalist (see Study One), can provide vegetative cover as well as contribute to a seed bank, and therefore, to the long-term process of community development.

The compost used in this study facilitated growth of both transplants and seedlings. Unexpectedly, it was also a repository of native and non-native seeds. Germination trials have shown that 23 species of plants, 18 of which are native to the Yukon, can be found in the sampled compost (data not shown). Some of these species are considered ‘weedy’ (i.e. those from the genera *Polygonum*, *Chenopodium, Hordeum*). However, all are naturalized around human-establishments and waste places throughout the territory (see Cody 2000). Weedy annuals do not tend to persist in natural environments in the Yukon (B. Bennett, pers. comm; Study One). As well, studies have demonstrated that short-lived species previously used in northern revegetation projects are often not detected or at least, their numbers have been significantly reduced in subsequent monitoring programmes (Withers 1999; Gretarsdottir *et al* 2004). Thus, these compost introduced plants could input organic matter, reduce fetch, and improve aesthetics while perhaps not presenting a long-term risk of introducing new non-native species into the succession. This conclusion, however, should be regarded as preliminary. It should be used with caution and involve continued monitoring. Perhaps the biggest advantage provided by this compost for Yukon mine tailings revegetation is that it is a local source and more importantly, it is available in relatively large quantities.

Cultivars of some native grasses adapted to northern conditions have been developed in response to the poor performance of introduced species and a recent emphasis placed on the use of native plants (ABR 1995). Many of these cultivars are commercially available and are currently used in northern revegetation projects (McKendrick 1997), including a variety of *D. caespitosa*, 'Nortran'. Nortran has been suggested for roadside revegetation and trench exploration sites and has been shown to successfully revegetate mine related disturbances in Alaska (Helm 1995). In these Alaskan field trials, Nortran demonstrated a remarkable ability to provide vegetative cover, but as a result, impeded subsequent colonization by local forbs and woody plant species. The plantings of *D. caespitosa* in this study actually increased invasion of plant species relative to chance colonization. The disparity in facilitative ability between this and the Alaskan study may be the result of differences in genetics or planting density due to variation in seeding and fertilizer application rates. Jochimson (2001), for example, found that the vegetative cover of grasses treated with fertilizer was denser than those of unfertilized plots and thus, air borne recruits were more prevalent in the latter. To the authors' knowledge, Nortran *D. caespitosa* has not been used for the revegetation of heavy metal laden mine tailings in the Yukon. The results of this study suggest that Nortran could well be successful in metal contaminated sites due to the demonstrated intrinsic metal tolerance of Yukon populations (Study Two). Because a commercial seed source exists, it is strongly recommended that trials which test Nortran on mine tailings containing potentially phytotoxic concentrations of heavy metals are undertaken in 2005. Pickseed Canada also lists *D. caespitosa* as one of their commercial grasses available for revegetation work and trials of this Canadian source should also be made in 2005.

There have been numerous successful tailings revegetation projects in the north. Their widespread application, however, is often minimal due to site-specific conditions. This study has tested the same populations of *D. caespitosa* and soil amendment treatments at sites which vary widely in pH, tailings texture, latitude, and chemical composition. The results demonstrate that, while there was no single population which performed the best at all three sites, all populations were capable of growing in each site, at least during the first two years of establishment (Table 4.4). Successful soil amendment treatments at each site were also delineated. Transplants of *D. caespitosa* grew and reproduced in unamended tailings and were in general hindered by the application of commercial fertilizer. In light of the negative fertilizer response, the benefit of the compost addition was likely a response to increased water retention, particularly since the summer of 2004 was hot and dry. Longer term studies are essential for restoration work and perhaps more so in the far north where growing seasons are short and growth rates are slow (Jorgenson and Joyce 1994). Long term perspective is, therefore, needed to determine the success of revegetation techniques to be evaluated for real productivity, stability, and reproduction rather than the short term response described to date.

General Conclusions

The natural and deliberate revegetation of Yukon mine tailings sites is challenged by adverse physical and chemical tailings conditions, as well as by the climatic extremes of the far north. The commonly used agricultural approach is often not conducive to long-term revegetation success at these northern sites. In this thesis, I assessed the potential role of the native grass, *Deschampsia caespitosa* in enhancing natural colonization and revegetating Yukon mine tailings sites. My goal was to follow a low-input approach by using potentially ecotypically adapted populations of *D. caespitosa*. I found that, at least in the short-term (two years), this low-input approach was working for each study site. To this end, I strongly recommend a continuation of research to test the additional species which were outlined in Study One, individually and in combination, based on the positive amendment trials, as well as to provide an assessment of longer-term success.

The analyses of tailings revealed elevated concentrations of heavy metals such as Cu, Cd, Ni, Fe, Pb, and Zn, as well as potentially toxic elements such as Al and As and low amounts of some essential plant nutrients (i.e. nitrogen and phosphorus) (Study One). The demonstration of intrinsic multiple metal tolerance in the five assessed Yukon *D. caespitosa* populations reduces the probability that elevated metal concentrations (i.e. Ni, Zn, and Cd) will impede the establishment of this species in metal laden tailings (Study Two). The fact that metal tolerance has also been shown in numerous *D. caespitosa* populations from Ontario and Europe to many metals and that this species has naturally colonized a wide variety of tailings sites also provides support for this conclusion. In terms of plant nutrients, I found that nitrogen and carbon (i.e. organic matter) were important in plant community development. Both of these variables explained a large portion of their respective axes in the ordinations and they were associated with later seral and more diverse plant communities. This suggests that the addition of organic matter, which also provides nutrients such as nitrogen (see Appendix C) will promote succession on the tailings.

The benefit of organic matter was shown in the field trials. Creating a seed bed is considered one of the most important factors for accelerating succession on mine tailings (Schultz and Weigleb 2000; Jochimsen 2001; Franks 2003). The compost used, from Whitehorse, was a seed repository of both native and naturalized species. At least in the short-term, these plants will contribute organic matter, help stabilize the tailings surface, and capture seeds of plants from adjacent habitats and thus, may enhance succession.

Growth and reproduction of the *D. caespitosa* transplants and seedlings was also improved by the compost amendment at all three sites. The compost would have improved water retention and supplied nutrients. It was difficult to assess the importance of adding nutrients for this species. A negative NPK fertilizer response was seen at Mount Skukum and United Keno Hill, while fertilizer was beneficial at Wellgreen. *D. caespitosa* was commonly found naturally inhabiting areas with lower nutrient levels and transplants in unamended plots tended to outperform those in fertilizer plots. This adverse response to fertilizer, therefore, may have been the result of fertilizer burn in plants adapted to poorer nutrient conditions.

Plants originating from northern (Chapin *et al* 1986) and arid (Piha *et al* 1995) climates and those from metal contaminated soils (Bradshaw and Chadwick 1980) frequently exhibit a low nutrient requirement for growth and reproduction. Indeed, Bradshaw has repeatedly seen a low nutrient demand, together with slow growth rates in his metal tolerant grasses of genera *Festuca* and *Agrostis*. In my studies, I found species, in addition to *D. caespitosa*, in the mine vicinity that have not yet invaded the tailings that were correlated to lower nutrients. These plants come from the shrubland and forested ecosystems, which generally had higher nutrient levels and greater species diversity. The association of these plants to lower nutrients is probable evidence of spatially heterogeneous nutrient distribution in surrounding habitats. Thus, while community development and diversity at these sites (i.e. MTSK and UKHM) corresponded to an increase in soil nitrogen, simply applying inorganic nitrogen is clearly not the solution to enhancing succession on the tailings, at least not for *Deschampsia* or likely for these additional species which correlated to lower nutrient levels.

The field trials demonstrated the remarkable ability of *D. caespitosa* to grow and reproduce in a climatically harsh, low nutrient environment. At all three sites, I found local and non-local populations that performed well in the untreated plots. At Mount Skukum, plants in untreated plots had a significantly higher mean score and produced significantly more flowers compared with other treatments. The local populations i.e. Mount Skukum and Annie Lake Road outperformed all other tested populations at MTSK and these populations also performed very well at United Keno Hill. I speculate that the highly mineral and drought prone soils of the Mount Skukum region have selected for extremely drought tolerant ecotypes of *D. caespitosa*. As well, Mount Skukum clones had a high absolute root growth in the hydroponic metal tests, suggesting that resources are diverted to root growth, a drought tolerant advantage. Thus, as observed by Jowett (1959), Gemmell and Goodman (1978) and Bradshaw and Chadwick (1980) there may be a mechanism that links metal tolerance, drought adaptation, and low nutrient requirements. To this end, selecting species which possess one or more of these qualities may provide a longer-term revegetation solution. Seemingly, *D. caespitosa* possesses all three of these attributes (see Study One).

The plantings of the field plots increased invasion of plants from adjacent habitats compared with chance colonization. This was most exceptional at United Keno where the colonization of *Agrostis sp.* and *Erigeron elatus* in the plot area was substantial. Grime *et al* (1988), from their extensive European studies, suggest that *D. caespitosa* is intermediately gregarious. The tufted nature of this plant, therefore, provides an opportunity for additional plant species to become established in the newly created microsites among plants. Incorporating a few additional nurse crop species into the revegetation programme as recommended by Luken (1990) and Wali (1999) will increase diversity and in turn, spatial (Tilman 1994) and temporal (McLaren *et al* 2005) heterogeneity will also be improved. To this end, improved heterogeneity will further enhance diversity and natural successional processes (Robinson and Handel 2000), creating a positive feedback and resulting in a low-input management approach for the revegetation of Yukon mine tailings sites.

Recommendations for Land Managers

Recent mine tailings revegetation workers in the north have emphasized the importance of using native plant species (e.g. Helm 1995; ABR 1995; Withers 1999). *The Yukon Mining Land Use Regulations* (MLUR) stipulates that a vegetative mat must be established using native plant species or other species adapted to the environmental conditions at hand. A Certificate of Closure will only be awarded when the mine operator has demonstrated that revegetation efforts are successful. Based on the results of this study, I recommend the inclusion of the native grass *Deschampsia caespitosa* as a nurse crop for the revegetation of hard rock mine sites in the Yukon Territory.

Yukon and Ontario populations of this species have demonstrated a remarkable ability to withstand a variety of harsh physical and chemical conditions as well as severe heat and drought. Populations originating from the Yukon are clearly pre-adapted to short growing seasons, poor nutrient status, semi-arid climate, and low temperatures and thus offer advantage over non-native species. Seed collections of *Deschampsia caespitosa* populations, particularly Mount Skukum and Annie Lake Road, for planting on drought prone and neutral to moderately acidic sites should be initiated for nursery production and future revegetation programmes. In contrast, Wellgreen and Kluane populations may be more appropriate for highly acidic tailings or tailings with widely fluctuating water tables.

In following a low-input approach, deliberately planting islands or buffers of *Deschampsia caespitosa* will encourage the invasion of additional species by increasing spatial heterogeneity of the tailings. This effect could also be achieved by non-randomly distributing woody debris. These islands will act as seed sources and sinks and will expand spatially over time (Franks 2003). Intentionally placing these islands in areas most susceptible to erosion will reduce the spread of contamination off the site as the roots of these grasses will help stabilize the surface. The establishment of vegetation will allow mine operators to remain in accordance with the *Yukon Quartz Mining Land Use Regulations* as well as with federal regulations such as the *Metal Mining Effluent Regulations (MMER)*.

The plant community assessments proved to be very insightful for future revegetation programmes. Species such as *Carex aquatilis*, *Epilobium angustifolium*, *Erigeron elatus*, *Equisetum arvense*, *Populus* and *Salix*, are principal candidates for future revegetation trials because of their affiliation with lower nutrients and/or exposed conditions. This outcome, in my opinion, speaks to the remarkable opportunity that spatial statistics offer restoration ecologists and land managers. It would be challenging, even for the best trained ecologist or naturalist to acquire this knowledge without long-term field study. Thus, by using a *spatial-chronosequence* and spatial statistics, land managers can interpret which environmental variables are most challenging to natural and deliberate revegetation and select species which may become established more readily with the least amount of amelioration. In turn, the probability of long-term success increases.

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Appendix A: List of species colonizing revegetation plots in summer 2004

Table B.1 Mean Number of Invading Plant Species in Revegetation Plots

Mount Skukum

Transplant Plots

no invasion

Seed Plots	**untreated**	**compost**	**fertilizer**	**mixed**	**control**
Achillea millefolium	.	.	.	6	.
*Chenopodium album**	.	67	.	58.5	.
Hordeum jubatum	.	2	.	1	.
*Matricaria matricariodes**	.	0.5	.	2.5	.
Polygonum sp.	.	2	.	.	.
Rorippa palustris	.	3	.	1.5	.
Taraxacum officinale	.	2.5	.	2	.
Total	**0**	**77**	**0**	**71.5**	**0**

United Keno Hill Mine

Transplant Plots

Colonizing species	**untreated**	**compost**	**fertilizer**	**mixed**	**control**
Agrostis sp.	8	15	1	.	7
*Chenopodium album**	.	.	.	4	.
Deschampsia caespitosa	7	14	4	4	1
Elymus trachicaulis	.	.	.	7	.
Epilobium angustifolium	12	14	1	2	.
Equisetum arvense	2	3		4	.
Erigeron elatus	6	.	3	1	5
*Hordeum jubatum**	36	21	30	6	.
Potentilla sp	.	1	.	.	.
Rorippa palustris	.	.	1	1	.
Salix glauca	.	1	.	.	.
Senecio leguns	.	.	.	1	.
Total	**71**	**69**	**40**	**30**	**13**

Seed Plots

Colonizing species	**untreated**	**compost**	**fertilizer**	**mixed**
Agrostis sp.	6.5	4	2	.
Capsella bursa-pastoris	.	4	.	.

*Chenopodium album**	.	7	.	21
Epilobium angustifolium	4	2	3	.
Erigeron elatus	2	.		4.5
Hordeum jubatum	3	12	5.5	3
Lepidium densiflorum	.	1	.	.
Matricaria matricariodes	.	5	.	4
Polemonium pulcherrimum	.	9	.	.
*Polygonum aviculare**	.	6	.	.
Potentilla sp.	.	2.5	.	2.5
Rorippa palustris	.	1.5	.	1.5
Senecio leguns	.	4	.	2
Unknown herb	.	13	.	2
Total	**15.5**	**71**	**10.5**	**40.5**

Wellgreen

Transplant Plots

Colonizing species	**untreated**	**Lime**	**compost**	**fertilizer**	**mixed**	**control**
Calamagrostis canadensis	.	.	.	0.5	.	0.5
Epilobium angustifolium	.	.	3	.	.	.
*Hordeum jubatum**	.	1.5	2	.	3.5	.
Total	**0**	**1.5**	**5**	**0.5**	**3.5**	**0.5**

Seed Plots

Colonizing species	**untreated**	**Lime**	**compost**	**fertilizer**	**mixed**
Artemesia sp.	.	.	0.5	.	.
Calamagrostis canadensis	.	.		.	1.5
*Chenopodium album**	.	.	1.5	.	1
*Hordeum jubatum**	.	.	6.5	.	2
Matricaria matricariodes	.	.	.	.	0.5
Potentilla sp.	.	.	.	.	0.5
Senecio leguns	.	.	3	.	2
Solidago simplex	.	.	1	0.5	2
Total	**0**	**0**	**12.5**	**0.5**	**9.5**

- Non-native species which are now considered naturalized in mosts areas of North America and the Yukon

Appendix B: Whitehorse Compost ICP-OES Analysis

Table C.1 Elemental Analysis for Whitehorse compost used in field revegetation trials. Values are a mean of three samples and represent total elemental concentrations (mg/kg). Carbon and nitrogen are the mean of three samples and are measured in percent (%) by weight.

Element	Mean Mg/kg
Ag	<2
Al	65000
As	<30
Ca	30000
Cd	<2
Cu	48.5
Fe	26500
K	16500
Mg	8550
Mn	555
Mo	<10
Na	22500
Ni	21.5
P	1750
Zn	92
%C	6.95
%N	0.57

Appendix C: Photographic Plates

Wellgreen

Plate 4. Plots at Wellgreen before July flooding

Plate 5. Wellgreen Plots during the July 2003 flood

Plate 6. Plots at Wellgreen in May 2004

Plate 7. *Deschampsia caespitosa* transplants in lime treatment 2003.

Plate 8. ***Polygonum amphibium ssp. laevmarginatum*** **(Water Smartweed) naturally colonizing the tailings pond perimeter.**

Natural colonization of tailings pond perimeter by grasses, sedges and other riparian zone plant species such as *Rumex arcticus* (Curled Dock). Tailings are identified in the soil chemistry as well can be visibly seen on soil surface.

United Keno Hill

Plate 10. Over view of Tailings impoundment

Plate 11. ***Deschampsia caespitosa*** **flowering in mixed amendment plot 2004**

Plate 12. ***Deschampsia caespitosa*** **in fertilizer plots 2004.** ***D. caespitosa*** **presence is largely reduced while 'weedy' species such as** ***Hordeum jubatum*** **(Foxtail barley) have become dominant.**

Plate 13. Compost seedling plots 2004: ***D. caespitosa*** **is the dominant grass seedling seen in the photo while the other species such as** ***Chenopodium album*** **(Lamb's quarter),** ***Sonchus sp*** **(Sow Thistle) have been contributed by the compost. Species such as** ***Hordeum jubatum*** **and** ***Erigeron elatus*** **have likely come in from surrounding plant communities**

Plate 14. Regrowth of *Epilobium angustifolium* (Common Fireweed) in unamended tailings 2004 from plantings in June 2003

Mount Skukum

Plate 15. Water damage from spring runoff in 2004

Plate 16. *Deschampsia caespitosa* in unamended tailings plot 2004. Transplants, excluding those from Wellgreen, performed the best in unamended tailings.

Plate 17. Natural colonization of *Epilobium angustifolium* (Common Fireweed) around tailings impoundment perimeter in 2003

Plate 18. *Deschampsia caespitosa* compost seedling plot in 2004: seeds of *D. caespitosa* planted in August 2003 did not germinate. This may have been the result of spring snow melt running through the seedling plots. *Chenopodium album* was dominant in all seedling plots which contained compost (i.e. compost and mixed amendment plots).

Plate 19. ***Deschampsia ceaspitosa*** **fertilizer plot in June 2004. All transplants were either dead or in extremely poor health**